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# FINAL TECHNICAL REPORT SATELLITE SERVICING ECONOMIC STUDY

December, 1990

Contract Number, NAS8-38142

Undertaken By  
**SPACE SYSTEMS/LORAL**  
Palo Alto, California

For The  
**NASA MARSHALL SPACE FLIGHT CENTER**  
**HUNTSVILLE, ALABAMA**

**SPACE SYSTEMS/ LORAL**

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**\* Formerly Ford Aerospace Corporation**

**SPACE SYSTEMS/ LORAL**

## ACRONYM LIST

<b>AXAF</b>	<b>Advanced X-Ray Astrophysics Facility</b>	<b>ODC</b>	<b>Other direct charges</b>
<b>C&amp;DH</b>	<b>Command &amp; data handling</b>	<b>OMV</b>	<b>Orbital Maneuvering Vehicle</b>
<b>CSSO</b>	<b>Communication satellite systems operations</b>	<b>ORU</b>	<b>Orbital replacement unit</b>
<b>DMS</b>	<b>Data management system</b>	<b>OTV</b>	<b>Orbital Transfer Vehicle</b>
<b>DMSP</b>	<b>Defence Meteorological Satellite Program</b>	<b>P(s)</b>	<b>Probability of success</b>
<b>DRM</b>	<b>Design Reference Mission</b>	<b>PED</b>	<b>Platform equipment deck</b>
<b>ELV</b>	<b>Expendable launch vehicle</b>	<b>POP</b>	<b>Polar Orbiting Platform</b>
<b>EOS</b>	<b>Earth Observation System</b>	<b>R</b>	<b>Recurring</b>
<b>EP</b>	<b>Explorer Platform</b>	<b>RMS</b>	<b>Remote Manipulator System</b>
<b>ESS</b>	<b>Expendable servicing system</b>	<b>SADA</b>	<b>Solar array drive assembly</b>
<b>EUVE</b>	<b>Extreme Ultraviolet Explorer</b>	<b>SATCAV</b>	<b>Stochastic space mission life cycle cost &amp; availability model</b>
<b>EVA</b>	<b>External vehicular activity</b>	<b>SSES</b>	<b>Satellite Servicing Economic Study</b>
<b>FSS</b>	<b>Flight Support System</b>	<b>SSF</b>	<b>Space Station Freedom</b>
<b>FTS</b>	<b>Flight Telerobotic Servicer</b>	<b>SSS</b>	<b>Satellite servicing system</b>
<b>GPBS</b>	<b>Geostationary Platform Bus Study</b>	<b>STS</b>	<b>Space transportation system</b>
<b>GSE</b>	<b>Ground support equipment</b>	<b>TDRSS</b>	<b>Tracking and Data Relay Satellite System</b>
<b>IOSS</b>	<b>Integrated Orbital Servicing System</b>	<b>WTR</b>	<b>Western Test Range</b>
<b>IVA</b>	<b>internal vehicular activity</b>	<b>XTE</b>	<b>X-Ray Timing Experiment</b>
<b>LCC</b>	<b>life cycle cost</b>		
<b>MACS</b>	<b>Modular attitude control system</b>		
<b>MMS</b>	<b>Multi-mision Modular Spacecraft</b>		
<b>MPS</b>	<b>Modular power system</b>		
<b>NR</b>	<b>Non recurring</b>		

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SPACE SYSTEMS/ **LORAL** —

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## **INTRODUCTION AND BACKGROUND**

This study was initiated by MSFC, in an attempt to consolidate previous servicing studies into a common database. In general, these studies have concluded that satellite servicing is a cost effective solution over an expendable satellite. The potential benefit of a consistent database of previous studies will provide a basis so that performance trends can be used when analyzing new servicing missions.

Space Systems/Loral (formerly Ford Aerospace Corporation) was tasked with collecting and reviewing the various program studies, and to apply the same methodology in an analysis of currently planned and funded programs. This would provide an independent cost analysis of new programs, and assess the overall life cycle cost benefits of servicing versus satellite replacement.

# INTRODUCTION AND BACKGROUND

SPACE SYSTEMS/ **LOREAL** —

- **Previous studies have shown that satellite servicing is cost effective**
- **However, all of these studies were of different formats, dollar year, learning rates, availability, etc.**
- **It was difficult to correlate any useful trends from these studies**
- **This study was initiated to:**
  - **Correlate the economic data from past studies into a common data base, using a common set of assumptions**
  - **Analyze a select set of existing funded programs to provide an independent analysis of the servicing options and potential economic benefits**

## STUDY TASKS

The goals of the study were to;

1. Review some of the previous servicing studies primarily as background data, and for life cycle cost (LCC) comparisons. The following programs were evaluated during the study. The Integrated Orbital Servicing System (IOSS), Spacecraft Assembly, Maintenance and Servicing, Satellite Servicing Working Group Studies, FAC/NASA studies on the Geostationary Platform Bus, Communication Satellite Systems Operations (CSSO) with the Space Station study, the Geostationary Platform Bus Study (GPBS), and the Defense Meteorological Satellite Program (DMSP) Block 6 study undertaken for the USAF. The data presented in these studies was transposed to a common data base and the costs normalized in 1989 dollars.
2. Develop new design reference missions (DRMs) that would be in place in the 1995 to 2010 time frame. The DRMs developed were for the Advanced X-Ray Astrophysics Facility (AXAF), the Polar Orbiting Platform (POPs), and the Explorer Platform. In general, four basic missions were established: Expendable, Expendable Servicing, Shuttle Servicing and Space Station Servicing. Shuttle and Space Station Servicing were not considered for the POP.
3. To conduct (a) a normalizing of the economic data of the selected scenarios from existing studies to produce life cycle costs (LCCs) and (b) economically analyzing the scenarios for the new DRMs. From this data, parametric curves were produced showing the sensitivity effects on the LCC by varying the satellite costs, reliability, servicer system cost and launch costs.

# STUDY TASKS

SPACE SYSTEMS/ **LORAL** —

- Review previous servicing studies and generate a common database normalized in 1989 dollars. Perform a life cycle cost (LCC) analysis for comparison with previously generated results.
- Develop new design reference missions (DRMs) in the 1995 to 2010 time frame. Examine the expendable satellite versus serviceable satellite option scenarios.
- Normalize the economic data for the selected expendable and serviceable scenarios to generate life cycle cost data. Generate parametric curves showing the sensitivity effects on the LCC by varying satellite costs, reliability, servicer cost, and launch costs.

## STUDY GROUND RULES

The common financial base was established in 1989 dollars. Any input or derived costs were escalated to FY89 dollars. The learning curve input was set at 100%, this was based on experience with the INTELSAT V Program (a total of 15 satellites) and discussions with NASA-MSFC on their experience with the Shuttle main engine program. The cost of money was set at a 5% discount rate for LCC results.

A 10% uncertainty factor was assumed in all final result data for comparing the economic benefit of servicing. This defined a confidence threshold in the results to establish when a servicing benefit had been realized. This factor was generated by examining the correlation data from Task 1, and from an estimate of the input data uncertainty for the Task2 DRMs considered.

The baseline ground rule used to estimate Shuttle costs is based on a charge of \$208M to launch 56K lbs to a nominal orbit of 160 nm, 28.5° inclination. This results in a \$3714 per pound. Then for the various missions, a table look-up is used to determine the capacity for other than 160 nmi altitudes orbits, and a new dollar-per-pound factor is determined. The 33% manifest charge is included for all Shuttle payloads if the weight and length of the payload do not represent over 75% of the Shuttle capacity.

Space Station servicing related costs are mission dependant, but all payloads will require handling, monitoring, integration and testing prior to the servicing mission. During the mission staging period ORUs will be monitored by the Station Crew and it is expected that these operations will require continuous support by the Space Station Freedom (SSF) Data Management (DMS) and Communications subsystems. The servicing mission will require IVA crew support, Remote Manipulator System (RMS) handling time, and possibly EVA. The cost estimates include SSF Logistics Pallet Use \$3,600/lb; DMS Services \$6,600/hr; Communications Services \$2,500/hr; RMS services \$41,700/hr; EVA activity \$123,000/hr; IVA activity \$19,000/hr.

# STUDY GROUND RULES

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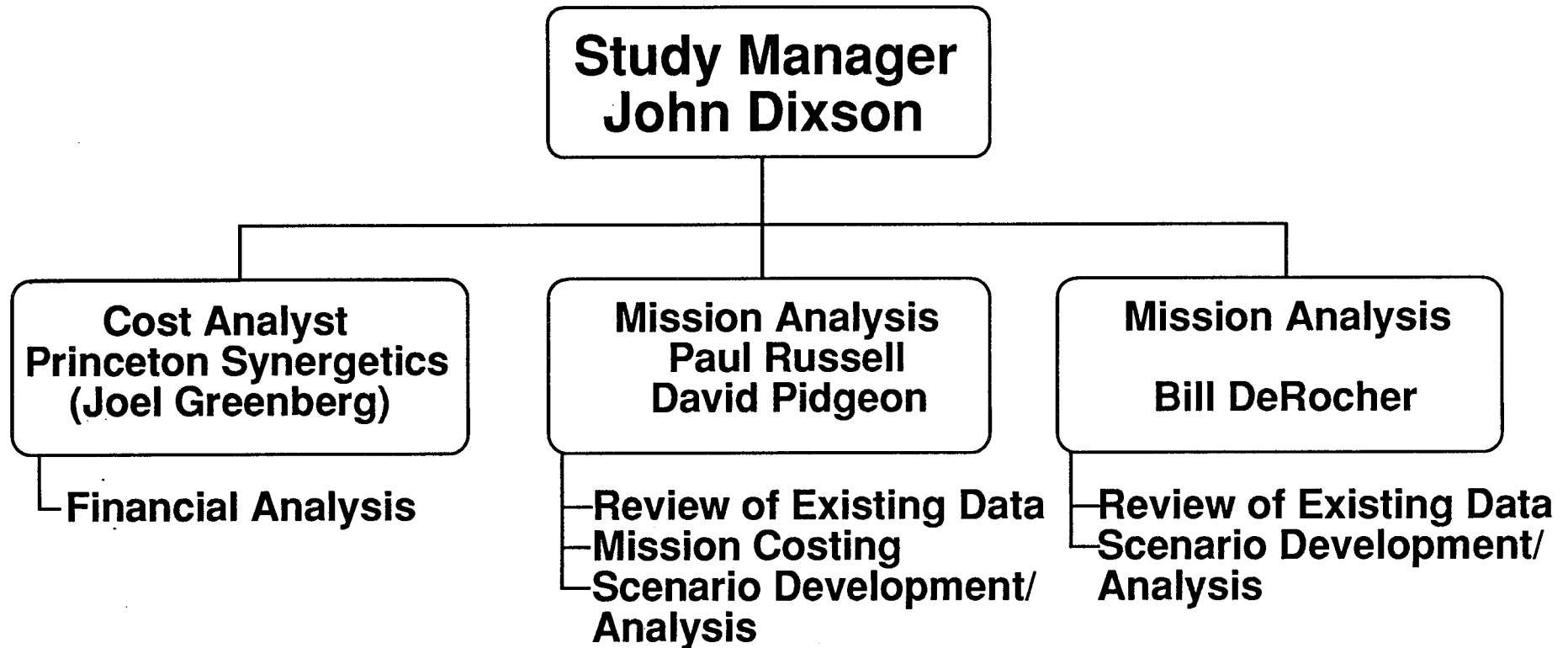
- All costs are in 1989 dollars
- Learning curve set at 100%
- Cost of money set at 5%
- A confidence threshold of 10% is used to evaluate the servicing benefit.
- System availability will be held constant.
  - Model will perform scheduled maintenance prior to failure
  - Model will simulate random failures and perform maintenance on demand
- Nominal Shuttle launch cost is \$208M to 160 nm orbit
- Space Station Freedom (SSF) user charges for servicing missions are mission dependant, and vary between \$10-30M. It is assumed that the servicing mission will require IVA and EVA crew support, Remote Manipulator System (RMS) handling, and SSF support services during payload integration and test.
- Development costs of NASA servicing systems are paid by the NASA. A user fee only is charged to each program
  - Remote servicer user fee: \$5M per mission
  - OMV user fee: \$6M per mission
  - OTV user fee: \$14.6M per mission plus fuel at \$2100/kg

## **STUDY ORGANIZATION**

The study was undertaken within the Advanced Systems Group of Space Systems Division (SSD) with the required support from the financial and contracts groups. Advanced Systems is a part of the Government Space Operations, headed by Mr Glynn Armstrong. Mr Bill DeRoucher, with many years of experience in the satellite servicing arena, was hired as a consultant primarily to undertake Task, 1 while Joel Greenberg, founder of Princeton Synergetics, provided the resources to generate the financial outputs utilizing the SATCAV computer model.

# STUDY ORGANIZATION

SPACE SYSTEMS/ **LORAL** —



## **SATCAV MODEL**

SATCAV; a stochastic space mission life cycle cost & availability model was developed by Princeton Synergetics, Princeton, NJ, and has been used as the prime analytical tool in this study to generate program life cycle costs.

The model simulates launch and on-orbit operations associated with the initiation and continuing operation of a generalized space mission comprising multiple satellites with a multiple sensor capability. The model operates on an IBM PC microcomputer and utilizes a LOTUS 123 menu driven input/output system to create a data-file that is accessed by a FORTRAN Monte Carlo program that performs the computation.

SATCAV simulates satellite launch operations using expendable or recoverable launch vehicles and upper stages and takes into account the consequences of a set of defined failures in terms of cost incurring events and time delays. SATCAV simulates the random and wearout of a multi-sensor satellite determining when specific failures occur and when maintenance actions are required to respond to critical failures.

SATCAV encompasses alternative maintenance scenarios that include both ground and on-orbit spares. Both launch on-failures and launch in-anticipation of wearout failure alternatives are available. Different transportation scenarios may be selected for placement and maintenance flights.

SATCAV also considers subjectively selected uncertainties and develops cost, event, and availability statistics reports. It also develops a typical event timeline report.

# SATCAV MODEL

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SPACE SYSTEMS/ **LORAL** —

- **SATCAV; a stochastic space mission life cycle cost & availability model is the prime analytical tool in this study to generate program life cycle costs.**
- **The model simulates launch and on-orbit operations of a multiple satellite system with multiple sensor capability.**
- **SATCAV simulates satellite launch operations using expendable or recoverable launch vehicles and accounts for the consequences of a set of defined failures in terms of cost incurring events and time delays.**
- **SATCAV simulates the random failures and wearout of a multi-sensor satellite determining when specific failures occur and when maintenance actions are required to respond to critical failures.**
- **SATCAV also considers subjectively selected uncertainties and develops cost, event, and availability statistics reports.**

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# SSES SUMMARY

SPACE SYSTEMS/ **LORAL** —

## DRM RESULTS

- **AXAF:**
  - All of the considered servicing scenarios showed to be cost effective over the expendable AXAF scenario. The expendable servicing system resulted in the lowest LCC
- **POP**
  - Platform servicing was not cost effective if total payload replacement is a requirement. A modified servicing strategy was defined to investigate when POP servicing would be cost effective.
- **EP**
  - The Expendable servicer demonstrated the lowest LCC. However, the Expendable servicer, Shuttle based servicer (FSS), and the expendable satellite scenarios were all within 5% in total LCC.

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# **TASK 1**

## **REVIEW DATA FROM EXISTING STUDIES**

## **TASK 1 METHODOLOGY**

A number of previous servicing studies were evaluated. As a basis for information two payload models were utilized to formulate the candidate servicing scenario. These were the 1973 NASA Headquarters and the 1974 NASA-MSFC payload models. These two sources resulted in a combined 545 mission and 101 payload programs. The 101 programs was reduced in the final count to 10. Having established the payload set the next step was to escalate the spacecraft and operational cost into 1989 dollars for a direct comparison of the LCC costs using the SATCAV model. Space Station costs were treated in a similar manner. Launch vehicle costs were also updated to reflect the current charges.

The data was then transcribed into the format required for the SATCAV model using the above assumptions and a number of test cases run. Once the inputs to the model for these test cases were refined and understood the balance of the cases were run. The results of these SATCAV outputs were then directly compared to the original study results normalized into 1989 dollars.

# TASK 1 METHODOLOGY

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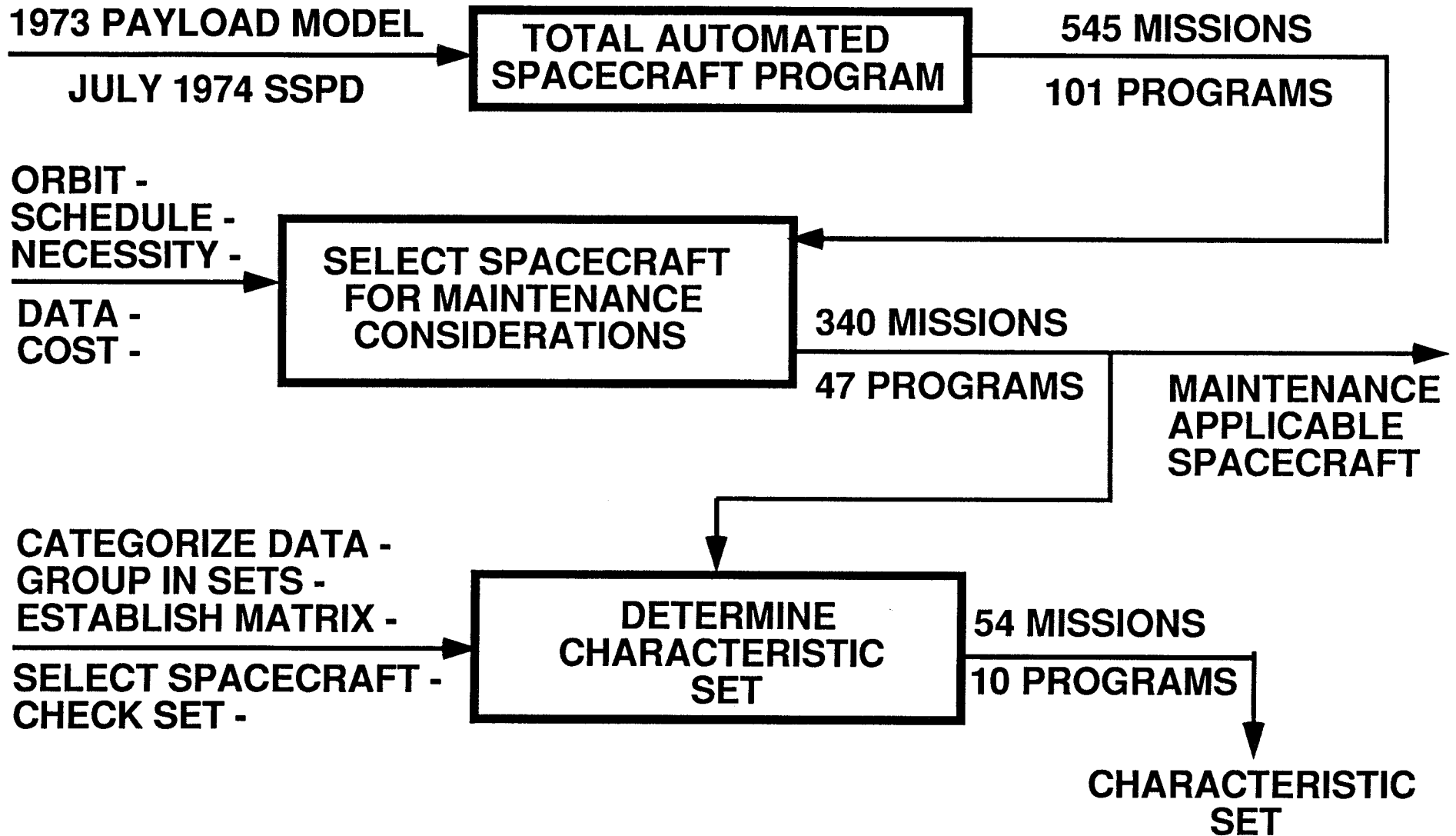
- Data for spacecraft and associated operational and maintenance costs for each mission analyzed were derived from previous studies
  - Spacecraft and operational costs escalated to 1989 dollars
  - Launch costs revised to reflect current launch vehicle charges
  - Space Station charges escalated to 1989 dollars
- Data transcribed to SATCAV format using described assumptions
- Results of SATCAV outputs compared to original study to determine similarities or differences

## **IOSS MAINTENANCE APPLICABLE SET SELECTION**

The following chart shows the selection logic in establishing the candidate payload set of spacecraft programs that could be used to test the value of servicing. The two NASA payload models combined for a total 545 missions and 101 programs. Using the criteria of orbit, which deleted the planetary missions, schedule, which deleted spacecraft in procurement, necessity, the need for servicing, data, sometimes only the program title was available, costs, which deleted low cost programs, the model was reduced to 340 missions in 47 programs. This set was further refined using the criteria shown to obtain a characteristic set with 54 missions in 6 programs. These six programs were used as the basis of representative conceptual designs and to provide specifics on the range of design data needed for other IOSS analysis.

# IOSS MAINTENANCE APPLICABLE SET SELECTION

SPACE SYSTEMS/ **LORAL** —



## **THE SSES/IOSS MAINTENANCE SET**

The next requirement was to reduce the 47 spacecraft programs of the IOSS maintenance set to the 10 programs of the SSES/IOSS maintenance applicable set. The main criteria was to identify programs where servicing would be cost effective.

The first 5 spacecraft eliminated were spin stabilized to which the IOSS cannot dock. Spacecraft with a recurring cost of less than \$40M in 1975 dollars was the next selection criteria used as studies have shown that servicing is unlikely to be cost effective on a low cost satellite. For the same cost effectiveness reason, satellites having a lifetime of less than 1 year were also eliminated. Programs with launch dates before 1980 or those whose mission were complete, and would, therefore, generate little or no interest, were dropped as were one flight or duplicate missions. Finally, the remaining 15 programs were placed in order depending on the model schedule launch date and the 5 earliest launch dates were deleted to bring the SSES/IOSS maintenance applicable set to 10 programs. This was viewed to be a manageable number that adequately spanned the range of orbital characteristics.

The chart identifies the 10 programs. The payload numbers are from the 1973 payload model and the payload code from the 1974 payload model. The missions range from astrophysics, code AST, Earth Physics, code PHY, and geosynchronous spacecraft, code NN/D (NN/D-14 is a LEO spacecraft).

# THE SSES/IOSS MAINTENANCE SET

SPACE SYSTEMS/ **LORAL** —

## 10 Program Set

<u>Payload Number</u>	<u>Payload Code</u>	<u>Spacecraft Name</u>
HE-08-A	AST-5B	Large High Energy Observatory A
HE-10-A	AST-5C	Large High Energy Observatory B
SO-02-A	AST-7	Large Solar Observatory
AS-16-A	AST-8	Large Radio Observatory A
HE-11A	AST-9A	Large High Energy Observatory D
AP-07-A	PHY-3B	Environmental Perturbation Satellite -B
CN-53-A	NN/D-2B	Domsat B
CN-59-A	NN/D-6	Communications R&D Prototype
EO-59-A	NN/D-12	Geosynchronous Earth Resources Satellite
OP-51 A	NN/D-14	Global Earth And Ocean Monitoring System

## **SPAN OF THE SSES/IOSS SET**

The ability of the SSES/IOSS maintenance applicable set to cover the range of important servicing characteristics (span of the set) is shown in this chart. The first characteristic of interest is the first launch date which spans from 1982 to 1988. The original IOSS maintenance applicable set spanned from 1979 to 1988. The difference occurred in the way the SSES/IOSS set was selected in-house. The second characteristic was orbit and the infrastructure required to attain it. For example, the Geosynchronous Earth orbit (GEO) satellites require an OTV to get to the final orbit. Polar orbits were excluded in this phase of the study since they were covered in Task2 with the POPs. The next characteristic was the satellite mass which covered a range from 957 kg to 9510 kg. As previously mentioned, low mass, less expensive satellites were eliminated during the SSES/IOSS set selection. However, the mass characteristic still covers a 10 to 1 range. The number of missions per satellite program in the SSES/IOSS span is from 2 to 14 as compared to the IOSS span of 1 to 25. Note that the SSES/IOSS selection process deleted the one mission programs and the 25 mission program was deleted because each mission's length was less than one year. The on-orbit fleet size of the SSES/IOSS set is from 1 to 7 while the IOSS span went from 1 to 12. The satellite program with 12 satellites on-orbit was deleted because of low satellite costs. The average lifetime for the IOSS set was from 0.5 to 6 years while that of the SSES/IOSS set was from 1 to 6 years. As previously stated, any program with less than one years life was disregarded.

The result of this is that the span of the SSES/IOSS set is more representative of spacecraft programs that have a higher probability of being cost effective with servicing than were those in the broader span of the IOSS set, which was intended to identify the bounds of cost effective servicing.

## SPAN OF THE SSES/IOSS SET

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Payload Code Number	First Launch Date	Orbit	Mass (kg) Exp S/C	Number Of Missions	On-Orbit Fleet Size	Life- Time (Yrs)
AST-5B	86	Orbiter	8400	3	1	1
AST-5C	87	Orbit	5034	2	1	2
AST-7	85	Orbiter	9510	7	1	1
AST-8	85	Tug-LEO	997	4	1	2
AST-9A	82	Orbiter	6470	4	1	2
PHY-3B	87	Tug-LEO	3947	2	1	3
NN/D-2B	82	GEO	1472	14	7	6
NN/D-6	83	GEO	957	3	1	4
NN/D-12	88	GEO	1531	10	2	2
NN/D-14	86	Orbiter	1289	9	3	2
SESS/Low	82	Orbiter	957	2	1	1
SESS/High	88	GEO	9510	14	7	6
IOSS/Low	79	Orbiter	141	1	1	0.5
IOSS/High	88	Polar	9731	25	12	6

**SPAN OF THE SSES/IOSS SET**  
**(Continued)**

No Text

## SPAN OF THE SSES/IOSS SET (Continued)

SPACE SYSTEMS/ **LORAL** —

Mission	Orbit	Mass (kg)	Constellation	Lifetime (Years)
CSSO	GEO	1335	2	10
GPBS	GEO	5040	3	10
Military METSAT	SSO	850	2	5
Military METSAT	GEO	905	1	5

## SPACECRAFT & SERVICER COST ESTIMATES

Spacecraft cost data were not listed in the IOSS published documentation as NASA had provided the cost data and felt that their release might compromise future procurement of the spacecraft. While these cost data may well be in NASA or Martin Marietta files, the difficulty in finding them was judged to be high. It was therefore decided to try and back out the cost numbers out of the expendable program costs, which were given in the IOSS documentation in 1975 dollars. The process followed is presented in the chart.

The expendable spacecraft equation involves 10 parameters plus the total. Each of these parameters is discussed and the approach to their quantification. Cost figures were obtained from the Integrated Orbital Servicing Study for Low Cost Payload Programs, Final Report, Volume II, Technical and Analysis, MCR-75-310, September, 1975, issued by the Martin Marietta Corporation, Denver, CO. The approach identified each cost component, or established a ratio between the cost component and the spacecraft recurring cost, thus leaving the recurring cost as the only unknown. Spacecraft recurring cost was assumed to be 5 times the spacecraft unit cost based on previous cost estimating ratios. The number of spacecraft were considered as was the loss factor during implacement. The next parameter was the ratio of launch check-out to spacecraft cost, taken in this case as 9%. Another parameter is the cost of sustaining engineering made up of three products, the cost per man year (40K in \$1975), the number of personnel retained for the recurring engineering, in this case 22 to 90. It was then necessary to estimate the number of personnel for each spacecraft program. This was calculated by estimating the spacecraft annual cost for each program. The largest annual space craft cost was divided by 90 to obtain a high ratio and the lowest cost divided by 22 to get a low ratio. The average ratio was then calculated. This average was then used with the annual cost to determine the number sustaining people for each program. The third factor in the product is the number of years that sustaining engineering is required. The next parameter is the launch cost sharing factor for the orbiter This factor must also be divided by 0.75 if the payload does not occupy more than 75% of the shuttle bay to account for manifesting because the orbiter will not be fully loaded. Orbiter launch costs must also be plugged into the equation. These were taken as \$12M in 1975 dollars. Other parameters considered were the cost of the tug (OTV) at \$1.1M in \$1975, a 0.85 tug user factor and the tug launch cost.

The servicer cost estimate was obtained from the 1975 IOSS Final Report and the final Final Report released in 1978. The second report was an effort to assure that nothing had been overlooked and emphasized operational costs. The first analysis used analogies to similar type manipulator systems to establish equipment costs on the basis of mass. Non-recurring costs were based on Martin Marietta's historical data. Three servicer units were produced, 2 for the East coast and 1 for the West coast. Spares included the equivalent of 3.5 units. Operations cost included 12 years at the ETR and 9 years at the WTR. All these inputs were then updated to 1989 dollars using inflation ratios provided by NASA-MSFC.

# SPACECRAFT & SERVICER COST ESTIMATES

SPACE SYSTEMS/ **LORAL** —

- Spacecraft costs not explicit in IOSS documentation
- Worked backwards from expendable spacecraft program
- Cost equation
- Expendable program cost values are documented
- Orbiter cost values are documented
- Tug cost values are documented
- Sustaining engineering
  - Used given range of 22 to 90 man levels to establish ratio to annual spacecraft program cost
  - Man year cost at \$40K
  - All other factors documented
- DDT&E to spacecraft unit cost ratio taken at 5
- Solved for spacecraft unit cost
- Solved for spacecraft DDT&E cost
- Used the IOSS ratios to serviceable spacecraft costs
- Servicer cost used data from first and second IOSS studies
  - Used analogies to similar systems and ratios for project engineering and management
  - Spares, logistics, ground support, facilities, and ops. site services included
  - DDT&E \$29M \$1975 (\$35M \$1977), Unit cost \$1.8M (\$2.2M \$1977), Ops. \$56.1M \$1975 (\$68.2M \$1977)
- Second analysis as check emphasized operations costs
  - DDT&E \$37.3M \$1977, Unit cost \$2.1M \$1977, Ops. (75% mission model) \$48.7M \$1977

## **SERVICING SCENARIO**

The missions compared remote servicing as opposed to a complete spacecraft replacement. No manned servicing capability was assumed for the geosynchronous or the Sun synchronous orbits.

Previous studies undertaken by Space Systems/LORAL (formally Ford Aerospace) such as the Communication Satellite System Operations with the Space Station (CSSO) study and the Geostationary Platform Bus Study (GPBS) assumed that the full NASA infrastructure defined at that time (1986/1988) would be in place at the time of the first launch. This infrastructure included a fully operational Space Station with Phase II assembly and servicing capabilities, including IVA and EVA, fuel storage and transfer, an Orbital Maneuvering Vehicle and the use of a space based Orbital Transfer Vehicle. Delivery to the Space Station was by means of the STS, which, in the case of the GPBS, included the External Tank Aft Cargo Carrier, or an expendable launch vehicle. The remote servicer was the IOSS, a scaled down version of the Orbital Spacecraft Consumables Resupply System (OSCRS), and the required ORU's.

The military METSAT did not utilize the Space Station and required an expendable servicing system.

# SERVICING SCENARIO

SPACE SYSTEMS/ **LORAL** —

- **Missions compared remote servicing versus spacecraft replacement**
  - **No manned capability for GEO or SSO**
- **CSSO and GPBS missions assumed full operational Space Station infrastructure**
  - **Transportation systems**
  - **Remote servicing systems**
- **Military METSAT assumed no Space Station and required an expendable servicing system**
  - **No return capability from SSO**

## **SUMMARY OF TASK 1 RESULTS**

The matrix on the opposite page is a summary of the results from the SATCAV model. These results included inputs for the cost of the satellite, launch and repair kit costs. Tabulated are the LCC cost for both the serviced and expendable case along with the resultant differences and percentage savings or increase.

# SUMMARY OF TASK 1 RESULTS

SPACE SYSTEMS/ **LORAL**

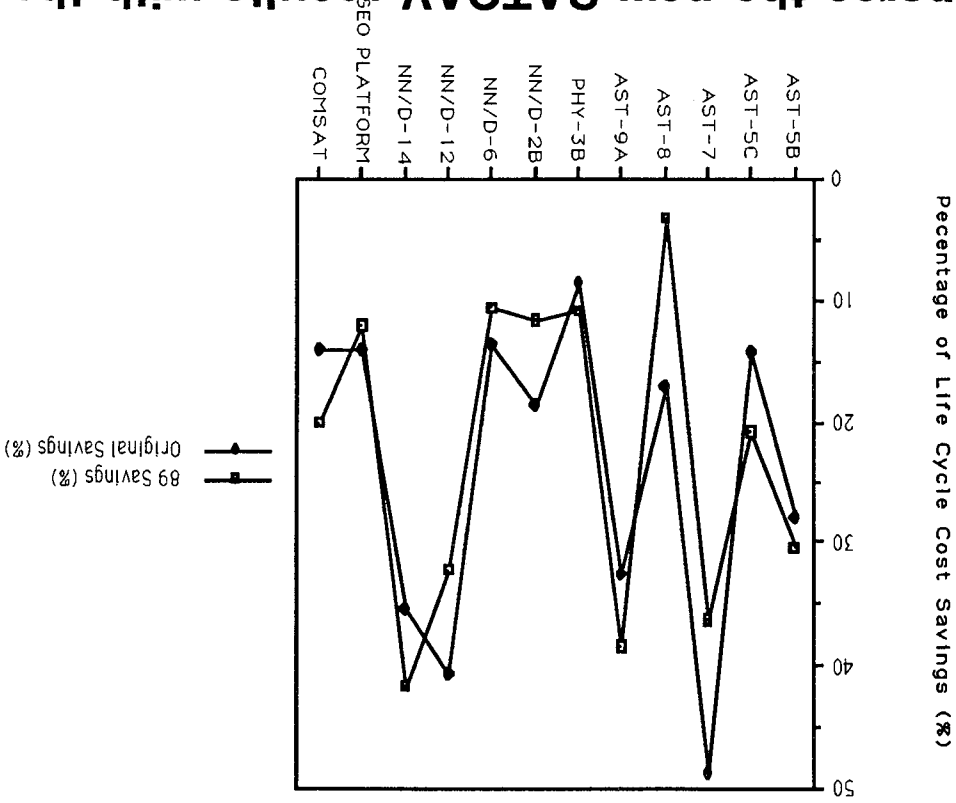
Program	Satellite Cost (\$M)	Satellite Lnch Cost (\$M)	Repair Kit Cost (\$M)	Life Cycle Cost (\$M)		Savings (\$M)	Savings (%)
				Non-Serviced	Serviced		
AST-5B	165.6	68.9	36.5	2553.1	1778.6	774.5	30
AST-5C	109.1	63.8	30.5	1420.5	1123.3	297.2	21
AST-7	210.7	118.9	41.3	3572.1	2277.7	1294.4	36
AST-8	57.4	219.4	36.2	2355.6	2277.4	78.2	3
AST-9A	168.2	83.9	36.8	3531.1	2177.3	1353.8	38
PHY-3B	100.2	236.1	41	2134.5	1904.6	229.9	11
NN/D-2B	76.2	130.5	43	3652.5	3227.4	425.1	12
NN/D-6	83	96.1	42.9	1675.3	1404.5	270.8	16
NN/D-12	91.2	136.2	34	4788.5	3250.9	1537.6	32
NN/D-14	87	57.8	26.1	3178.6	1854	1324.6	42
GEO PLATFORM	850	212	733	7488	6564	924	12
COMSAT	70	65.4	44.6	845	675	170	20
METSAT-L	40	60	45	681	717	-36	-5
METSAT-G	100	107.7	47.1	1273	1180	93	7

## **COMPARISON OF SSES RESULTS**

As can be seen from the comparative curves on the opposite page, the percentage savings between the the original studies and those generated using the SATCAV model compare fairly closely.

# COMPARISON OF SSES RESULTS

SPACE SYSTEMS/ LORAL



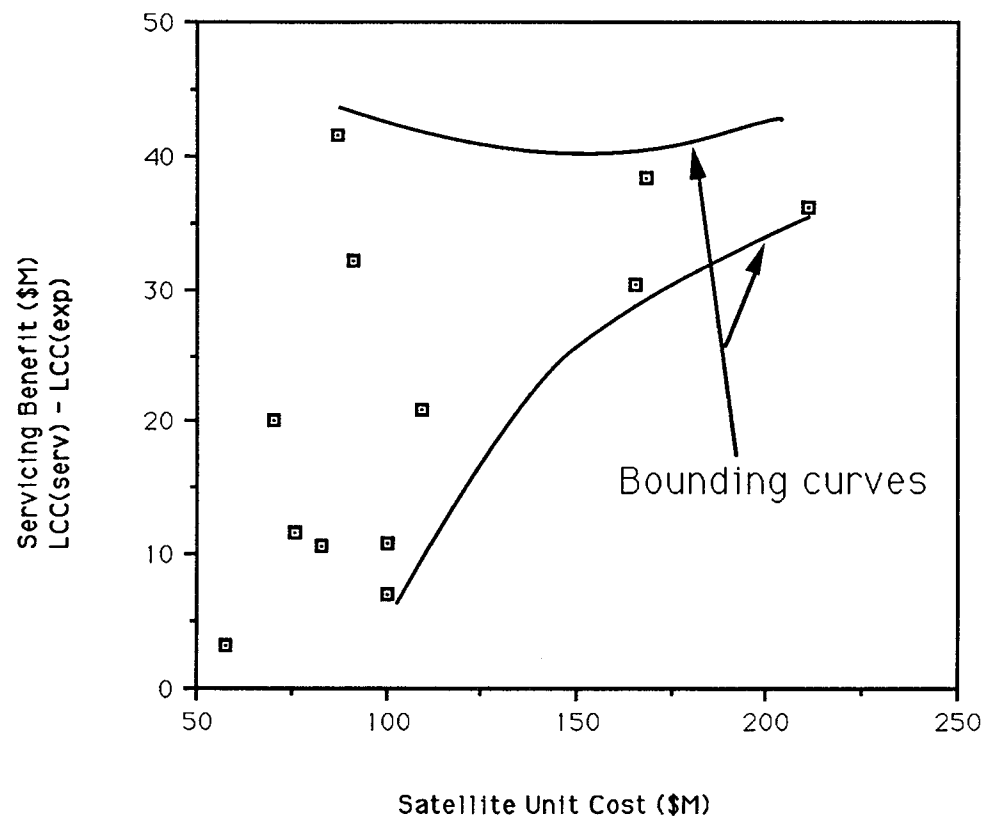
- This chart compares the new SATCAV results with the previous study results.
- The AST-7, and AST-8 were separated by about 15%. The SATCAV model initiated more repair missions and replaced the spacecraft to achieve the mission availability over the life of the program. The number of servicing missions initiated is highly sensitive to the input reliability data.
- Overall, the SATCAV model results are within 5% of the predictions of the older studies.

## **LCC SAVINGS Vs SATELLITE COST**

Although there is a large amount of scatter in the points on this curve an attempt was made to bound the points with a 'mean' line. The result was that a more realistic interpretation was a max/min curve. Even so, these curves show that as the satellite costs increase the benefit of servicing increases.

# LCC SAVINGS Vs SATELLITE COST

SPACE SYSTEMS/ **LORAL**

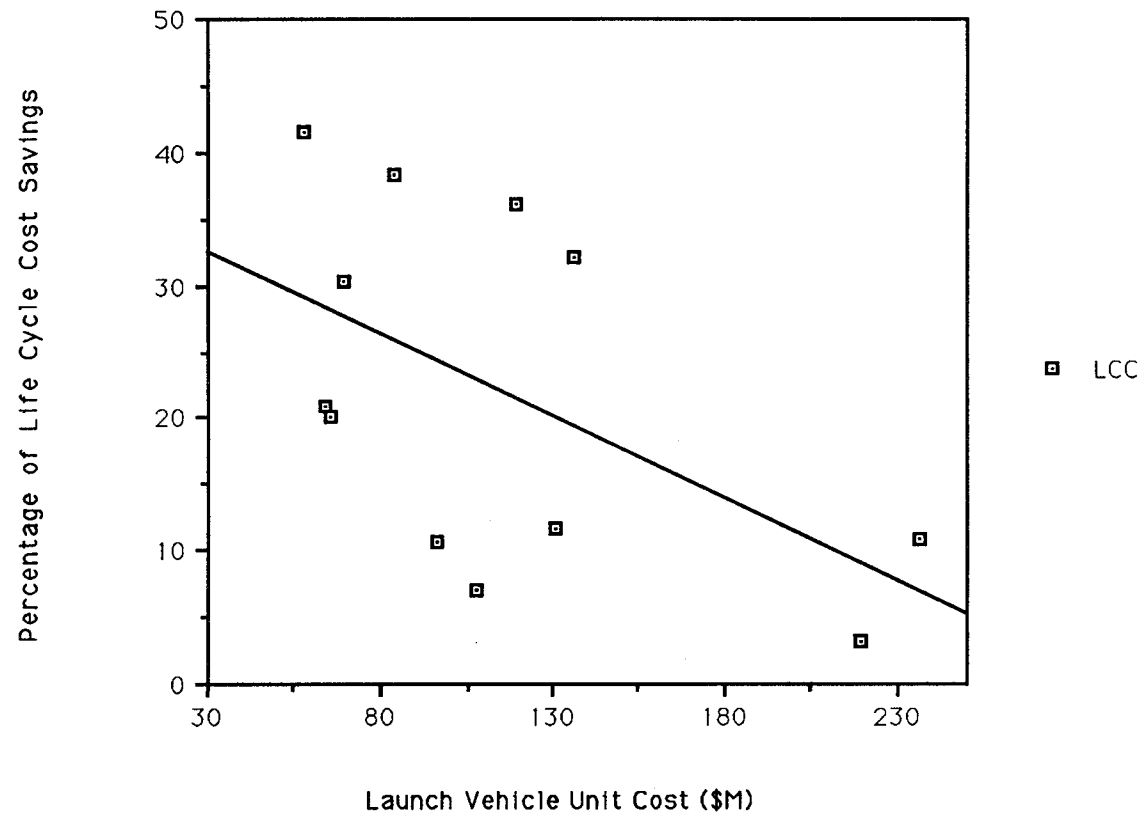


## **LCC SAVINGS VS. LAUNCH COST**

The curve on the facing page is a plot of the percentage LCC savings versus launch unit cost. As can be seen there is a sizeable amount of scatter in the points but there appears to be a mean position where a line can be plotted as is shown. It can be seen that as the launch cost increases the benefit of servicing decreases.

# LCC SAVINGS VS. LAUNCH COST

SPACE SYSTEMS/ **LORAL**



## **TASK 1 CONCLUSIONS**

The average benefit in the LCC costs due to servicing is 19.6%. This indicates that there is potential benefit in providing the servicing capability in certain satellite programs. However, the standard deviation of the results is about 14.4% indicating a large spread in the data. This leads to the conclusion that the benefit of servicing is not overwhelmingly conclusive and each program must be analyzed on a case by case basis.

Although the resultant data produced sizeable scatter, the trend indicates that the more costly the unit price of the satellite the more benefit there is to building in a servicing capability. The results indicate that the maximum cost benefit of servicing appears to be about 35%. Another benefit of servicing is in the number of satellites. As the number of satellites increases, the benefit of servicing increases.

The cost of launching a servicing mission must also be considered. The results of the study show that as the launch cost increase the benefit of servicing decreases. However, all in all, the results of this study effort track reasonably well with previous studies. It is clear that for some missions servicing will provide savings in the LCC.

# TASK 1 CONCLUSIONS

SPACE SYSTEMS/ **LORAL** —

- **Average savings in life cycle cost due to servicing is 19.6%**
  - **Indicates strong potential benefit due to servicing**
- **Standard deviation of above result is 14.4%**
  - **Indicates large spread in data**
  - **Servicing must be analyzed on a case by case basis**
- **Trend indicates that as the satellite unit cost increases, the benefit of servicing increases**
  - **Maximum benefit of servicing is approximately 35%**
- **As number of satellites increases, the benefit of servicing increases**
- **Trend indicates that as the satellite launch cost increase, the benefit of servicing decreases**
- **Results of the 1989 analysis track reasonably well with previous results**

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## **TASK 2**

**ANALYZE NEW DESIGN  
REFERENCE MISSIONS**

## **TASK 3**

**ECONOMIC ANALYSIS**

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## **TASK 2 AND TASK 3 COMBINED**

Task 2 and Task 3 are presented together for each of the 3 DRMs examined. This increases the flow of the data from scenario development through analysis and results.

Task 2 Develop the servicing versus replacement scenario for each of the 3 design reference missions (DRMs). The DRMs developed were for the Advanced X-Ray Astrophysics Facility (AXAF), the Polar Orbiting Platform (POPs), and the Explorer Platform. In general, four basic missions were established. Expendable, Expendable Servicing, Shuttle Servicing and Space Station Servicing. Shuttle and Space Station Servicing were not considered for the POP.

Task 3 normalizes the economic data of the selected scenarios and analyzes the data in a parametric manner. The parametrics show the sensitivity effects on the LCC by varying either the satellite cost, reliability, servicer system cost or launch cost.

# **TASK 2/ TASK 3 COMBINED**

SPACE SYSTEMS/ **LOREAL** —

## **Task 2: ANALYZE NEW DRMs**

- **Develop servicing and expendable scenarios**
- **Format cost mass and reliability data**

## **Task 3: ECONOMIC ANALYSIS**

- **Use SATCAV model to generate program LCC**
- **Show sensitivity of reliability and cost components on overall LCC**

**Design Reference Missions Included: AXAF, POP, EP**

## **AXAF**

This DRM represents one of the 4 great observatories. The Advanced X-ray Astrophysics Facility (AXAF) mission is designed to collect astrophysical data over a wide range of the electromagnetic spectrum. The spacecraft is configured for a Shuttle launch to a 325 nm orbit. The spacecraft has no on board propulsion and over a 5 year period the orbit will degrade to 293 nm assuming nominal solar activity.

The AXAF spacecraft is designed for a 15 year mission with in-situ servicing every 5 years. During these servicing periods, it is expected that the servicing vehicle will perform a velocity maneuver to re-boost the satellite to a 325 nm orbit.

# AXAF

SPACE SYSTEMS/ **LORAL** —

<b>Mission:</b>	<b>Astrophysics</b>
<b>Mission Duration:</b>	<b>15 Years</b>
<b>Constellation:</b>	<b>1 Satellite 28.5° X 325 nm orbit.</b>
<b>Launch Vehicle:</b>	<b>STS</b>
<b>Spacecraft Dry Mass:</b>	<b>30,000 lbs</b>
<b>Spacecraft Cost:</b>	<b>\$525.0 M</b>

## **CANDIDATE SERVICING SCENARIOS**

The 5 candidate scenarios shown on the facing page were identified for further investigation. These scenarios were selected on the basis of their potential for reducing the cost of operating the AXAF spacecraft over the mission life. More detailed descriptions of the scenarios and their evaluation is presented later in the report.

# **CANDIDATE SERVICING SCENARIOS**

**SPACE SYSTEMS/ LORAL** —

- 1. Servicing at the Space Station utilizing OMV for retrieval**
- 2. Servicing in-situ utilizing a Space Station based SSS**
- 3. Servicing in the Shuttle bay utilizing the OMV for retrieval**
- 4. Servicing in-situ utilizing the ground based SSS**
- 5. Servicing in-situ utilizing the ESS**

## **SPACE STATION BASED SERVICING CONSIDERATIONS**

If the OMV and SSS can be based at the Space Station a potential savings launch costs of up to \$59M can be realized. These savings are due the fact that each user will not be charged for transporting the OMV or SSS to orbit. Space Station based servicing scenarios for low altitude spacecraft have one major disadvantage. The orbital mechanics impose short windows of opportunity followed by long periods during which the spacecraft will be inaccessible from the Space Station. These consideration are summarized on the facing page. The orbital mechanics of Station based servicing will be discussed in subsequent charts.

# SPACE STATION BASED SERVICING CONSIDERATIONS

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SPACE SYSTEMS/ **LORAL** —

- Station based servicing scenarios will reduce launch charges by as much as \$59 M.
  - Savings will be dependent on methodology of OMV propellant resupply
- Nodal alignment of AXAF and Space Station must be within 3°

## **SPACE STATION BASED SERVICING, OMV PERFORMANCE**

Two of the candidate scenarios involved Space Station based servicing missions. The first of these scenarios involved a remote servicing mission utilizing a Space Station based SSS. The second candidate scenario was a retrieval scenario where the satellite would be retrieved from its orbit with a Station based OMV, and transported to the Space Station for servicing. After servicing, the satellite would be returned to orbit with the Station Based OMV. Since both of these missions involve the OMV, an analysis was performed to determine the capability and limitations that the orbital mechanics would impose on the system scenarios..

The difficulty in Station based servicing lies in the fundamental orbital mechanics of an inclined orbit. The oblateness of the Earth produces a torque on the line of nodes which, at space station based orbits, act in the opposite direction of the orbital motion. This phenomena, known as nodal regression, is a function of the orbit inclination and radius. This implies that satellites at different altitudes and inclinations will have different rates of nodal regression. The effect of differential rates of regression is shown in the chart on the facing page.

For the AXAF mission, the differential nodal regression rate, difference between space station orbit and AXAF orbit, is on the order of  $0.27^\circ/\text{day}$  (assuming AXAF degrades from 320nm to 293nm over 5 years). Given the maximum propellant capacities of the OMV, this places extreme constraints on the servicing window of opportunity. The servicing window will be discussed in subsequent charts.

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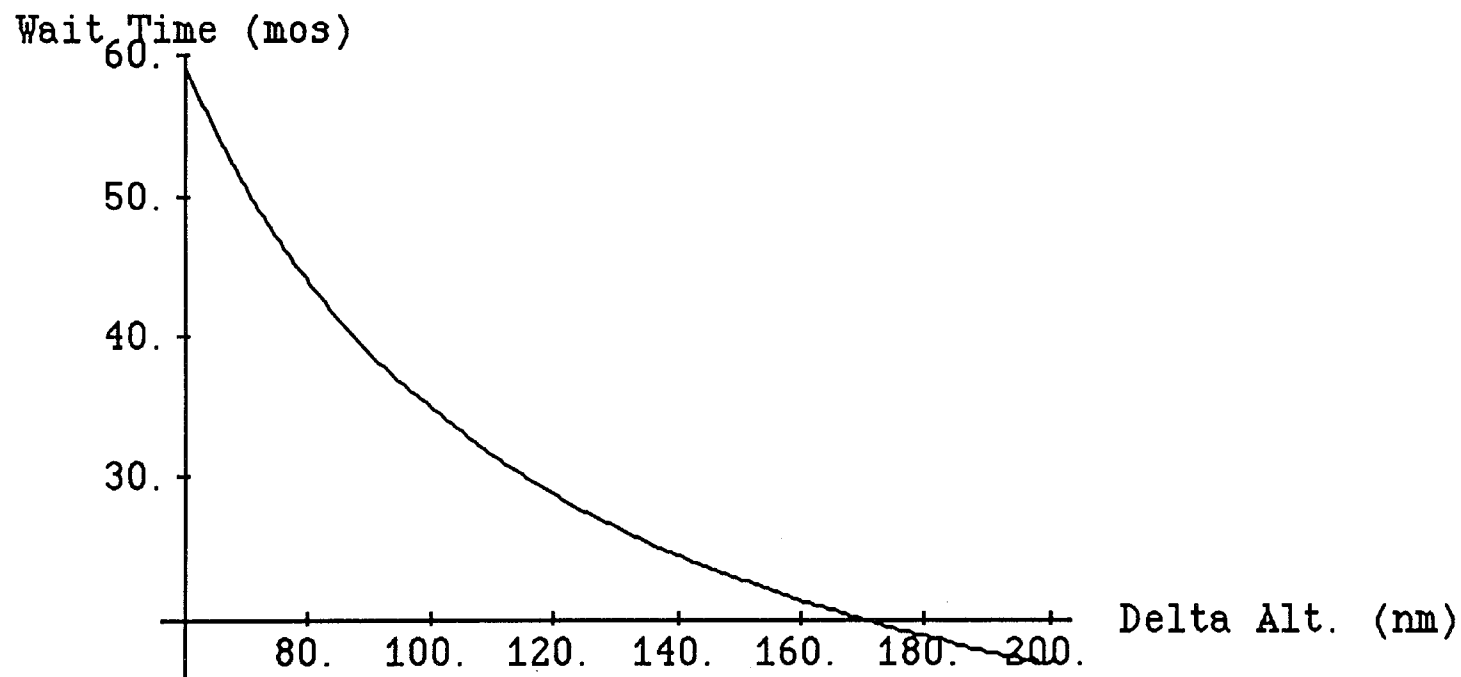
## ALIGNMENT WAITING TIME AS FUNCTION OF DELTA ALT.

The chart below plots the waiting period between successive nodal alignments, as a function of the difference in altitude between the space station orbit and the AXAF orbit. If the space station is assumed to be located in a nominal 240 km orbit, then the differential altitude will vary between approximately 53 nm to 80 nm. This will result in a waiting period between successive nodal alignments in the order of 40 - 45 months. Due to this slow nodal drift, approximately  $8.4^\circ$  per month, a 15-20 day window of opportunity will exist to rendezvous and service the AXAF within a  $\pm 3^\circ$  nodal bandwidth. The larger the nodal bandwidth the larger the window of opportunity, but the lower the transfer mass capacity. This window of opportunity estimate assumes that both orbits are at the same inclination. Initial orbit dispersions and second order orbit perturbations will result in inclination changes between the space station and AXAF. The next few chart plot the OMV capabilities for orbit altitude/inclination, and servicing scenarios. No attempt has been made to quantify the potential second order effects, however, a follow-on mission analysis parametric study could be performed, if requested.

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# ALIGNMENT WAITING TIME AS FUNCTION OF DELTA ALT.

SPACE SYSTEMS/ **LORAL** —

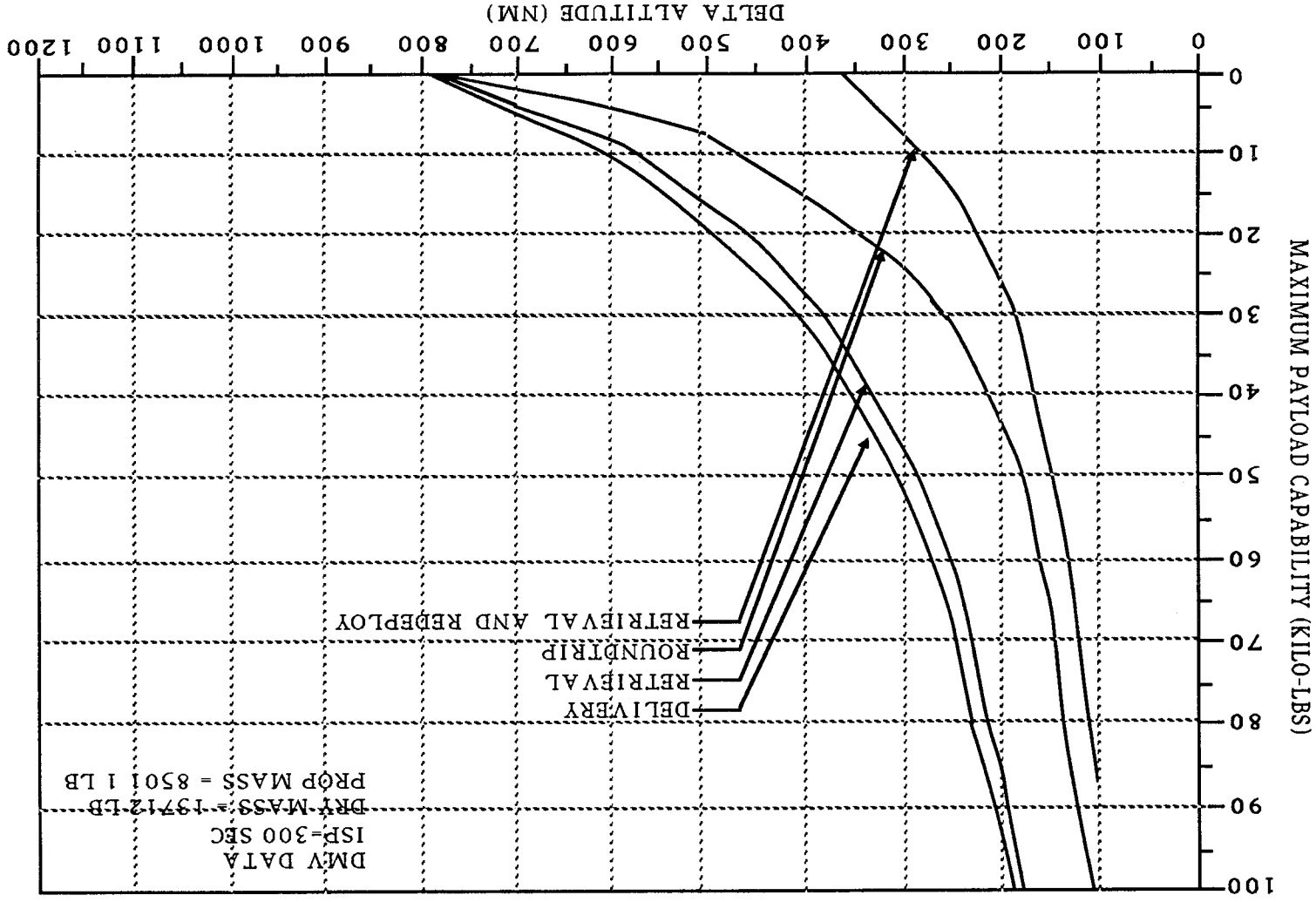


## **OMV PERFORMANCE CHARACTERISTICS (NO PLANE CHANGE)**

The chart on the facing page illustrates the performance capabilities of the OMV with the Propulsion Module. It shows the OMV capability for four servicing options. It assumes however, that the maneuver is performed when the space station and AXAF are coplanar (ie. same orbit inclination and nodal alignment). The delivery curve assumes that the OMV delivers the payload to its final orbit, whereas, retrieval assumes that the OMV rendezvous with the payload at its orbit location and delivers it back to the station. The retrieval and redeploy would describe the scenario when the AXAF is brought back to the station for servicing, and redeployed to its final orbit after servicing.

# OMV PERFORMANCE CHARACTERISTICS (NO PLANE CHANGE)

SPACE SYSTEMS/ LORAL

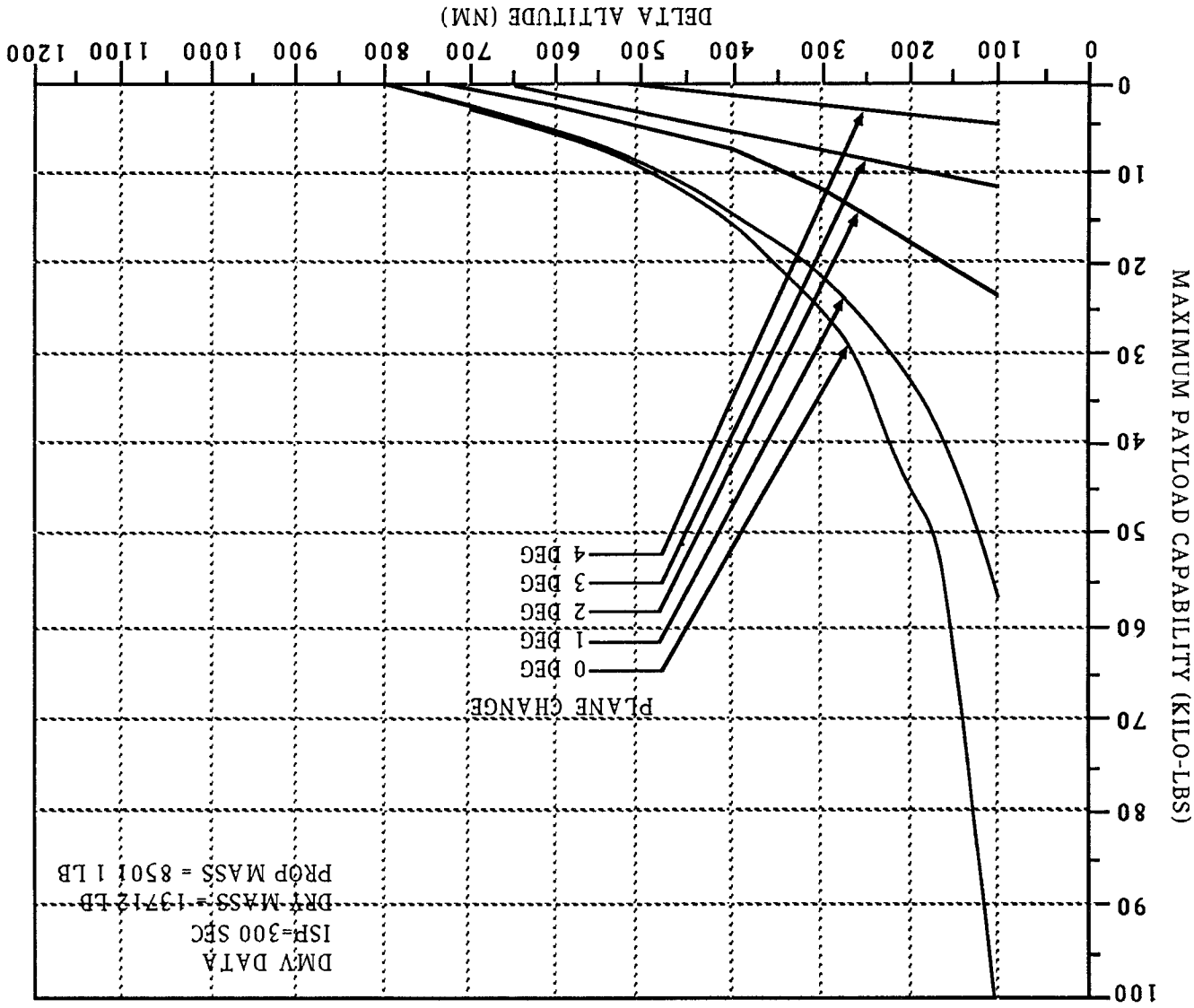


## **OMV PERFORMANCE CHARACTERISTICS (MISSION PAYLOAD ROUND TRIP)**

The chart on the facing page illustrates the performance capabilities of the OMV for a round trip mission with a 13,712 lb payload and inclinations of up to 4 degrees. The chart shows that servicing is possible, provided that the nodal alignment is within 3 degrees.

# OMV PERFORMANCE CHARACTERISTICS (MISSION PAYLOAD ROUND TRIP)

SPACE SYSTEMS/ LORAL

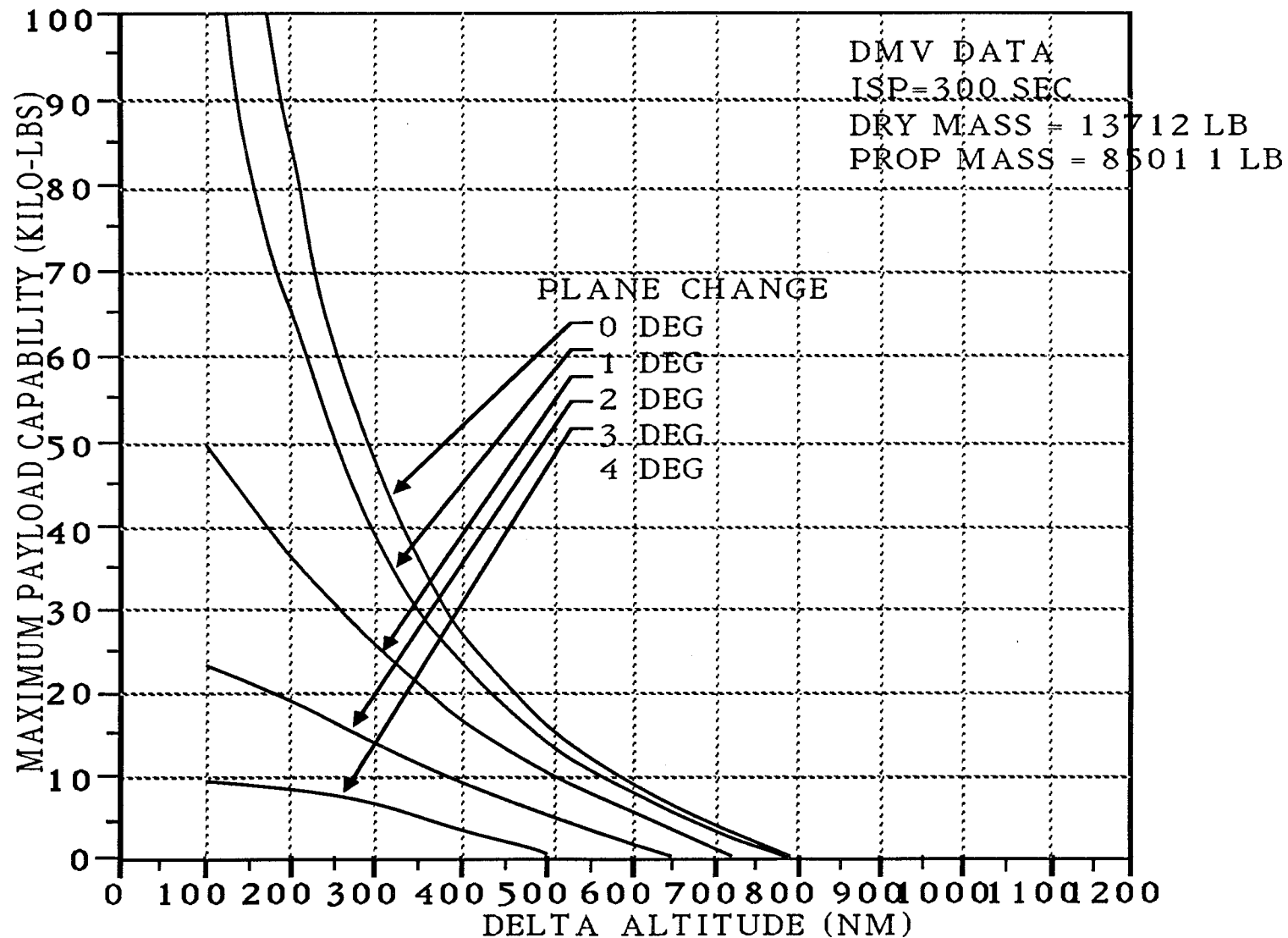


## **OMV PERFORMANCE CHARACTERISTICS (MISSION PAYLOAD RETRIEVAL)**

The chart on the facing page illustrates the performance capabilities of the OMV for a retrieval mission with a 13,712 lb payload and inclinations of up to 4 degrees. The chart shows that retrieval is well within the capabilities of the OMV, provided that the nodal alignment is within 3 degrees.

# OMV PERFORMANCE CHARACTERISTICS (MISSION PAYLOAD RETRIEVAL)

SPACE SYSTEMS/ **LORAL** —

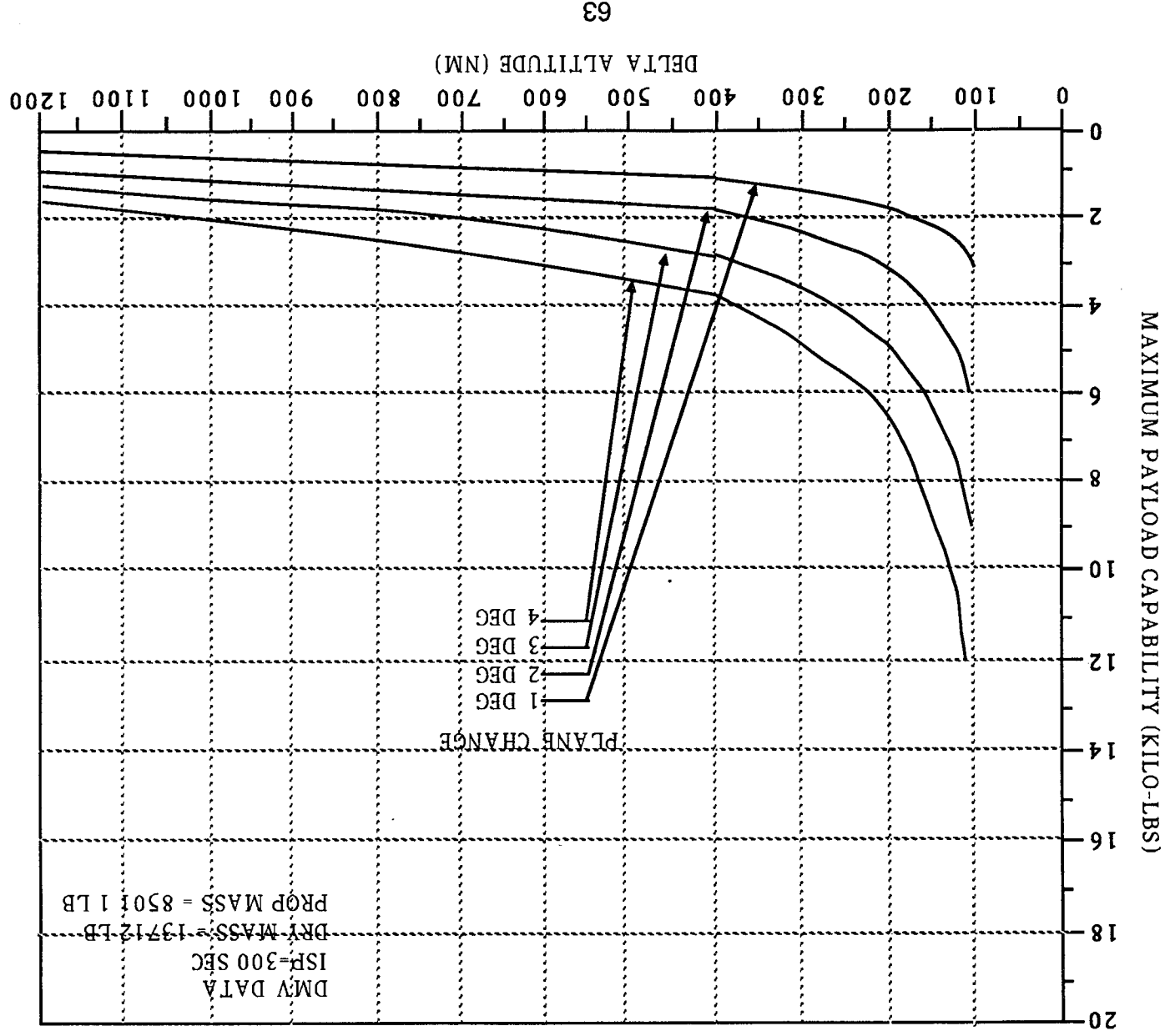


## **OMV SERVICE WINDOW**

The chart on the facing page illustrates the potential servicing window for the AXAF servicing mission. Given a maximum plane change capability of 3 degrees and delta altitude of approximately 70 nm, it is seen that the service window is approximately 12 days. This means that the servicing mission must occur within a 12 day period or it will be delayed by approximately 52 months. Given the workload on the Space Station crew, launch vehicle manifesting difficulties and potential for OMV failures, this imposes a severe constraint on Station based servicing.

# OMV SERVICE WINDOW

SPACE SYSTEMS/ LORAL



## **TYPICAL SERVICING COMPLEMENT**

Trades performed during the Phase-B study indicated that the platform components could be divided into 3 categories:

1. Orbital Replaceable Units (ORUs)
2. Contingency Replaceable Units (CRUs)
3. Replenishable Units (RUs)

Although the spacecraft design will allow on orbit servicing of any component with the exception of the cabling, only the ORUs are scheduled for replacement. The servicing mission will consist of the components shown on the opposite page. The total replacement cost of these components will be \$289M, assuming that there is no ground refurbishment.

# TYPICAL SERVICING COMPLEMENT

SPACE SYSTEMS/ **LORAL** —

ORU	Mass	Units Req	Total Mass
Science Instrument 1	965	1	965
Science Instrument 2	710	1	710
MPS Module	625	2	1250
C&DH Module	445	1	445
Reaction Wheels	120	3	360
Inertial Ref. Units	38	2	76
SI Electronics	50	2	100
SI Gas Bottle	50	2	100
Solar Arrays	705	2	1410
Total	3708	16	5416

- **Total ORU Cost is \$289M per servicing mission.**

## **ESTIMATED SPACE STATION COSTS**

It is expected that the servicing payload consisting of the OMV fuel and AXAF ORUs will be transported to the Space Station Freedom (SSF) approximately 2 weeks prior to the servicing mission. During the mission staging period the ORUs will be monitored by the Station Crew and it is expected that these operations will require continuous support by the SSF Data Management (DMS) and Communications subsystems. The servicing mission will require crew support on the order of 200 hrs of IVA and 10 hrs EVA. These estimates cover the ORU checkout, servicing mission support and SSS integration. It is also estimated that SSS integration will require up to 10 hrs of Remote Manipulator System (RMS) handling time. The cost of these services is shown on the facing page. It should be noted that both of the proposed SSF based servicing scenarios assume the existence of a SSF based OMV and/or SSS. In addition, potential user charges for Flight Telerobotic Servicer (FTS) have not been included.

The costs shown in the chart on the facing page are for the in-situ servicing mission based from the Space Station. The cost for a retrieval mission is expected to be more than double that for the in-situ mission because of the dramatic increase in the amount of EVA and IVA labor required to perform the ORU exchange operations. The estimated cost for servicing the AXAF at the Station will be on the order of \$65M which is in excess of the potential STS launch savings of \$59M. Based on the added complexity and lack of cost savings, servicing of the AXAF spacecraft at the space Station was dropped from the list of candidate scenarios.

# ESTIMATED SPACE STATION COSTS

SPACE SYSTEMS/ **LORAL** —

Service or Task	Unit Estimate	Units Reqd.	Cost (\$M)
SSF Logistics Pallet Use	\$3,600/lb	5,500	19.8
DMS Services	\$6,600/hr	336	2.2
Communications Services	\$2,500/hr	336	.8
RMS services	\$41,700/hr	10	.4
EVA activity	\$123,000/hr	10	1.2
IVA activity	\$19,000/hr	200	3.8
Power	\$220/kwhr	336	.1
Total Cost			28.3

- Assumes SSS is based at Space Station (not baseline for Station)

## **GROUND BASED SERVICING CONSIDERATIONS**

The ground based servicing missions are not subjected to the severe launch window constraints as the SSF based scenarios. Although ground based servicing systems require transportation to orbit each time they are used, the addition flexibility in launch windows offsets the potential cost savings of Space Station based scenarios. Further, the considerations of Expendable Servicing Systems explores the potential for utilizing less expensive launch vehicles.

# GROUND BASED SERVICING CONSIDERATIONS

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SPACE SYSTEMS/ **LORAL** —

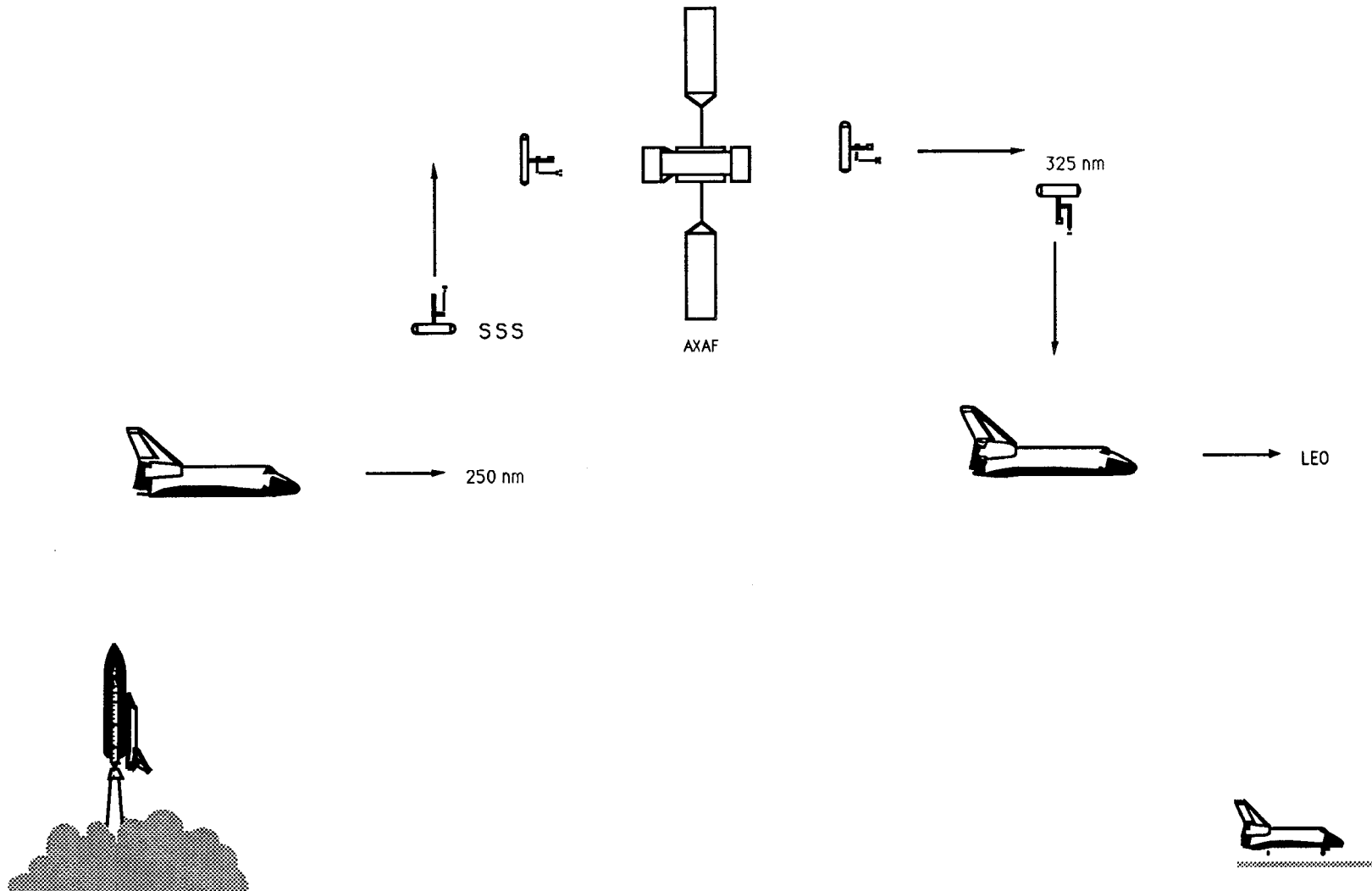
- Servicing equipment must be transported to orbit each time they are used
- Greater operational flexibility
  - Less severe launch window constraints
  - Servicing can be performed "on demand"
- Expendable scenario allows use of less expensive launch vehicles

## **AXAF SSS SERVICING SCENARIO**

The SSS servicing scenario pictured on the following page uses the STS to transport the SSS to a 280 nm orbit. The OMV/SSS system would then rendezvous with AXAF and the SSS would perform the servicing operations using its robotic capabilities. Upon completion of the servicing operations, the OMV would reboost AXAF to its original orbit. After this maneuver has been completed, the OMV will return to the STS for capture and stowage for return to the ground.

# AXAF SSS SERVICING SCENARIO

SPACE SYSTEMS/ **LORAL**

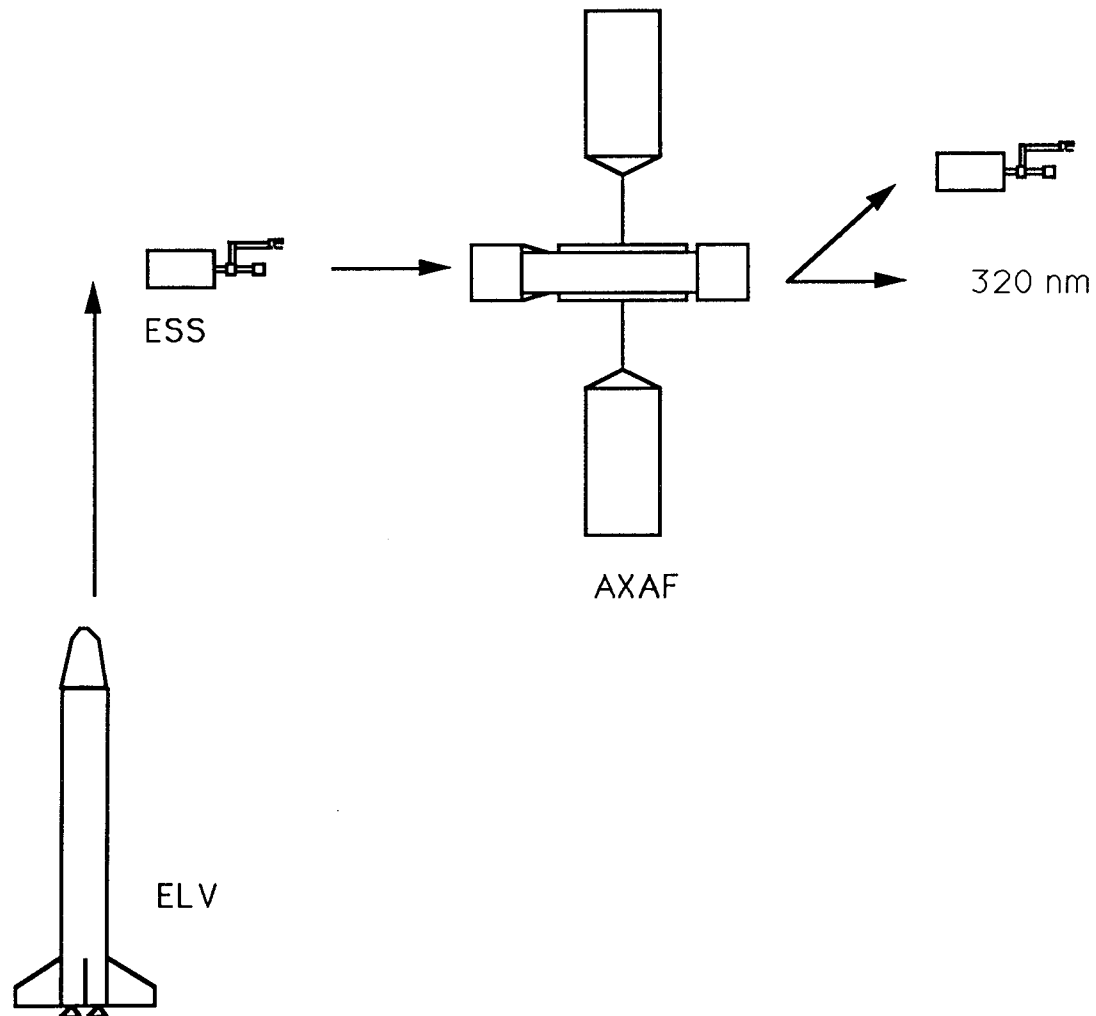


## **AXAF ESS SERVICING SCENARIO**

The ESS servicing scenario pictured on the following page uses an ELV to transport the ESS to a 320nm orbit. The ESS would then rendezvous with AXAF and would perform the servicing operations using its robotic capabilities. Upon completion of the servicing operations, the ESS will perform a reboost maneuver to return AXAF to its original orbit. After the reboost has been completed, the ESS will be placed in a disposal orbit.

# AXAF ESS SERVICING SCENARIO

SPACE SYSTEMS/ **LORAL**

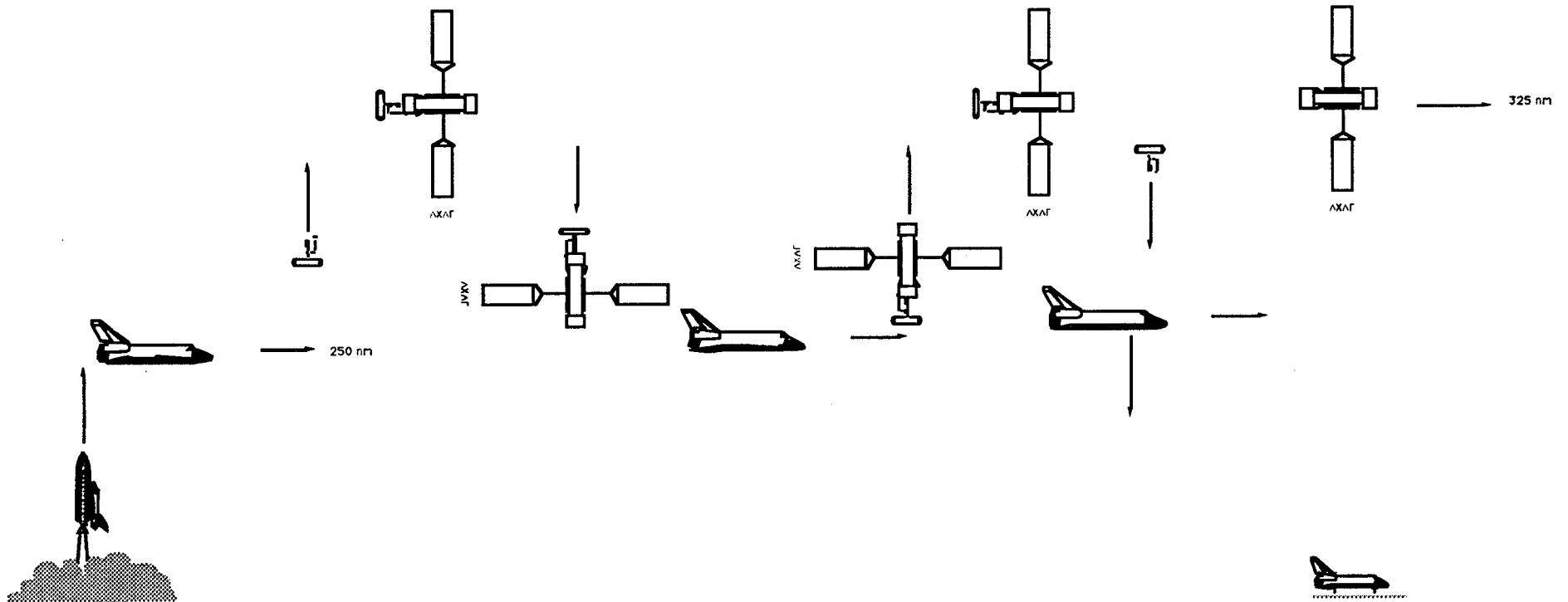


## **AXAF EVA SERVICING SCENARIO**

The EVA servicing scenario pictured on the following page utilizes the STS to transport the OMV to orbit. The OMV is then used to retrieve the spacecraft to the Shuttle bay. The servicing operations are performed in the shuttle bay by EVA astronauts with support from the Astronaut Aid and RMS robotic systems. Following the servicing operations, the OMV returns the spacecraft to its 320 nm orbit and returns to the Shuttle. The placement and retrieval operations can be performed using the OMV fitted with the Propulsion Module without additional refueling on orbit.

# AXAF EVA SERVICING SCENARIO

SPACE SYSTEMS/ **LORAL**



## **SERVICING SCENARIO SELECTION CRITERIA**

Prior to performing the economic analysis, the five candidate scenarios were evaluated to determine their relative performance. Each of the scenarios was ranked in terms of mission cost, risk and complexity. Once each of the scenarios had been ranked, a down select was made based on their relative ranking in terms of the these three factors.

Both of the space station based scenarios suffered from a high risk due to the short servicing window and long period between servicing opportunities. The combinations of these two factors virtually eliminates the possibility of performing an emergency servicing mission should a catastrophic spacecraft failure occur. In addition, the additional complexity of handling the servicing equipment at the Space Station is an added step that is unnecessary. Further, if the servicing system and ORUs were transported to the Space Station, the potential reductions in launch costs would be eliminated and these scenarios would be even less attractive. Finally, the high cost of the Space Station operations also increase the cost of these scenarios because of the additional handling steps (removal from STS, checkout and integration w/OMV/SSS). Overall these scenarios received the lowest ranking and thus were dropped from the candidate set.

The ground bases scenarios generally received higher marks in all three categories. The remote servicing options were viewed to have the lowest complexity because of the reduced number of OMV operations. In terms of risk, the ground based retrieval scenarios was seen to be the lowest because of the high level of human involvement in the servicing operations. Past experience on the MMS program has demonstrated the human ability to improvise and perform delicate operations that would be impossible for a robotic or telerobotic system to perform. The retrieval scenario was found to have additional launch costs due to the added mass of the Flight Support System and OMV fuel. In addition the cost of EVA will push the mission cost even higher. Based on the cost and complexity considerations the retrieval scenario was dropped from the candidate set. It should be noted that the expendable scenario received the highest marks. This is largely due to the ability to use a lower cost launch vehicle.

# SERVICING SCENARIO SELECTION CRITERIA

SPACE SYSTEMS/ **LORAL** —

Scenario	Cost	Risk	Complexity
SSF Based In-Situ w/ SSS	Med	Hi	Hi
SSF Based Retrieval	Hi	Hi	Hi
Ground Based Retrieval	Hi	Lo	Hi
Ground Based SSS	Med	Med	Lo
Ground Based ESS	Lo	Med	Lo
Selected Set			

## **SERVICING MISSION MASS SUMMARY**

The servicing mission mass breakdown is shown on the facing page. It should be noted that the servicer mass shown includes the servicing vehicle, robotic servicer and any ASE. The propellant calculations represent the necessary fuel to rendezvous with the AXAF during the servicing mission. The row titled "other" represents a mass margin for the ESS and SSS case, and represents the Shuttle cradle weight to stow the servicer and replacement ORUs during launch.

# SERVICING MISSION MASS SUMMARY

SPACE SYSTEMS/ **LORAL** —

Servicing Equipment	Mass (lbs)		
	SSS	ESS	EVA
ORUs	5416	5416	5416
Servicer (dry)	13994	1257	13994
Fuel	3683	300	7200
Other	560	250	9220
Total	23653	7223	35830

## **SATCAV COST INPUTS**

The chart on the facing page illustrates the key recurring cost inputs to the SATCAV model. The costs shown have the most significant contribution to the resultant life cycle cost. The spacecraft and ORU cost inputs were derived from the AXAF Phase B estimates. Since AXAF is baselined for servicing, the non-serviced spacecraft cost was estimated to be 10% less than the Phase B cost. This figure was arrived at from the results of previous studies which indicates that serviceability increases the spacecraft cost by 10%. The spacecraft launch charges were based on a STS launch. It should be noted that the non-serviceable spacecraft launch charges are lower because its estimated mass was 8% lower than the corresponding serviceable spacecraft.

The ORU charges were derived from the Phase B study cost estimates for the projected servicing mission payload complement. The SSS servicer costs were based on the standard OMV and SSS user charges of \$6M per mission and \$5M per mission, respectively, plus an additional \$4M in crew training and operational expenses. The SSS launch costs were based on a STS launch. The ESS servicer costs were based on a recurring servicer cost of \$30M plus \$4M in crew training and operational costs. The ESS cost was derived from an internal study which determined that a low cost mission specific servicer could be manufactured for \$30M, assuming that the design could draw on key technologies from previous programs such as the FTS, SSS and the OMV. The ESS launch charges were based on a Delta II launch.

Other costs which were input to the model but are not shown in the chart include:

1. Payload operations cost of \$31.5M per year which was used for all 3 cases.
2. A sustaining engineering cost of 2% of the spacecraft recurring cost.
3. A non-recurring spacecraft cost of 10% of the spacecraft recurring cost.
4. A servicer non-recurring cost of \$24.3M and SSS.

It should be noted that the model requires all costs to be entered as a maximum, minimum and distribution of the cost uncertainty. The cost shown are nominal costs. The model inputs were the nominal cost +/- 10% with a gaussian uncertainty distribution.

# SATCAV COST INPUTS

SPACE SYSTEMS/ **LOREAL**

Expenditure	Cost (\$M)			
	Expendable	SSS	ESS	EVA
<b>Original Satellite Costs</b>				
Satellite	525	583	583	583
Satellite Launch	169	180	180	180
<b>Total</b>	<b>694</b>	<b>763</b>	<b>763</b>	<b>763</b>
<b>Servicing Costs</b>				
ORU	N/A	289	289	289
Servicer	N/A	15	30	7.5
Servicing Launch	N/A	129	52	193
<b>Total</b>	<b>N/A</b>	<b>433</b>	<b>371</b>	<b>490</b>

## **SATCAV MODELLING INPUT ASSUMPTIONS**

Since SATCAV is Monte Carlo model, it requires input on the reliabilities of the spacecraft, the launch vehicles and the servicer. In order to masking of the results by the reliability data, the probabilities of success (Ps) for the servicer and launch vehicles were set to the standard values indicated earlier in the report. These probabilities were agreed upon with NASA at the beginning of the study.

The AXAF Phase B study indicated that the projected servicing interval was 5 years and the spacecraft would have a Ps of 0.44 at that time. With a Ps of 0.44, the SATCAV model predicted a much shorter servicing interval and since it was felt that the 5 year interval was in good agreement with past experience the Ps inputs were adjusted to 0.77 for the entire spacecraft. Since the spacecraft is designed to be almost completely serviceable the Ps for the servicing mission was set to 0.88. This number is the combination of a probability of repairability of the spacecraft of 0.9 and Ps of the servicer of 0.98.

# **SATCAV MODELLING INPUT ASSUMPTIONS**

SPACE SYSTEMS/ **LOREAL** —

- **Cost data derived from AXAF Phase B Study, and escalated to FY89 dollars**
- **The AXAF phase B study indicated that the projected servicing interval was 5 years with a spacecraft Ps of 0.44**
- **To maintain good agreement with past experience the SATCAV model system reliability was adjusted to 0.77**
- **The Ps for the servicing mission was set to 0.88. This number is the combination of a probability of repairability of the spacecraft of 0.9 and Ps of the servicer of 0.98.**
- **The Shuttle launch charges are based on a sliding scale based on launch weight relative to launch capacity to orbit. The secondary payload approach is not considered. (see Shuttle cost methodology in the EP DRM section for description of costing procedure)**

## AXAF RESULTS

The facing page shows the results of the AXAF economic analysis. Shown are some of the key model inputs as well as the calculated number of satellites and number of repair kits required to perform the mission and the life cycle cost. The life cycle cost shown is the 5% discounted cost. The numbers shown in the table are the average values calculated by SATCAV. The standard deviations on each of the life cycle costs is approximately 10% for all cases.

The output data indicate that 4.6 platforms are required for the expendable scenario, and that 1.4 platforms/3.0 servicing missions are required to maximize the overall availability over the 15 year mission lifetime. The interpretation of the number of platform or servicing mission, as shown below, is the modelling implementation of spreading the costs of a new platform or servicers. No modelling techniques are incorporated to stop the implementation of a new platform or servicer near end-of-life if a failure occurs. So if a failure does occur near the end of the mission lifetime, then a percentage of the replacement cost is spread over the remaining mission years.

It was considered a fair assumption that the EVA case could always be serviced, and therefore, only 1 platform would be required. However, for the expendable launched missions, the model used the probability of repair data ( $P_s = 0.9$ ) to specify if a servicing failure could occur. Therefore, even though the system availability remained approximately unchanged, the complement of replacement missions to service missions were not identical.

# AXAF RESULTS

SPACE SYSTEMS/ **LORAL** —

Scenario	Satellite Cost (\$M)	Sat. Launch Cost (\$M)	Repair Kit Cost (\$M)	Rep. Launch Cost (\$M)	Number of Satellites	Number of Repairs	Life Cycle Cost (\$M)
Non-Serviced	525	169	N/A	N/A	4.6	N/A	2364
SSS Serviced	583	180	308	129	1.4	3.0	2039
ESS Serviced	583	180	323	52	1.4	3.0	1938
EVA Serviced	583	180	338	193	1.0	3.4	2116

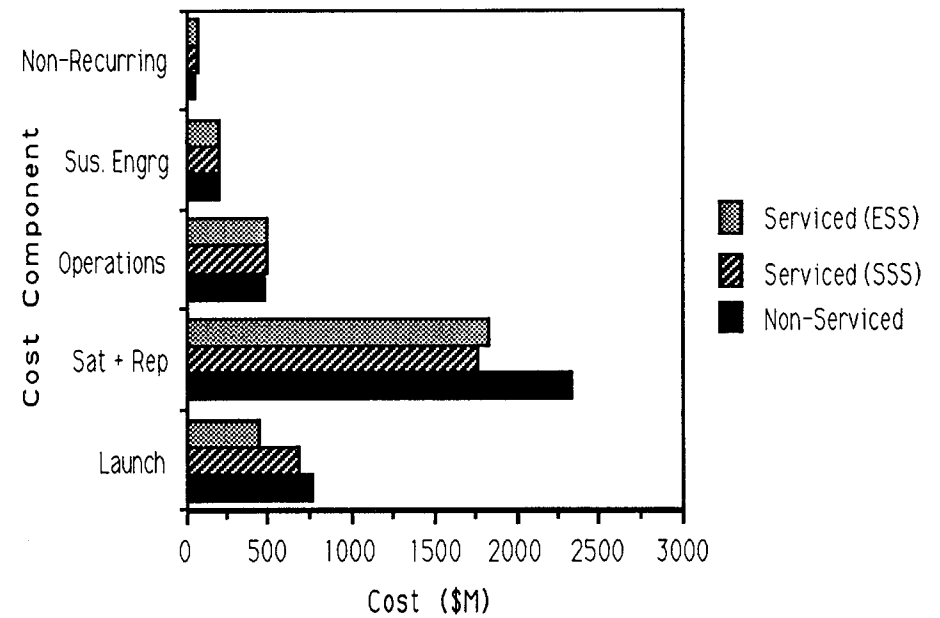
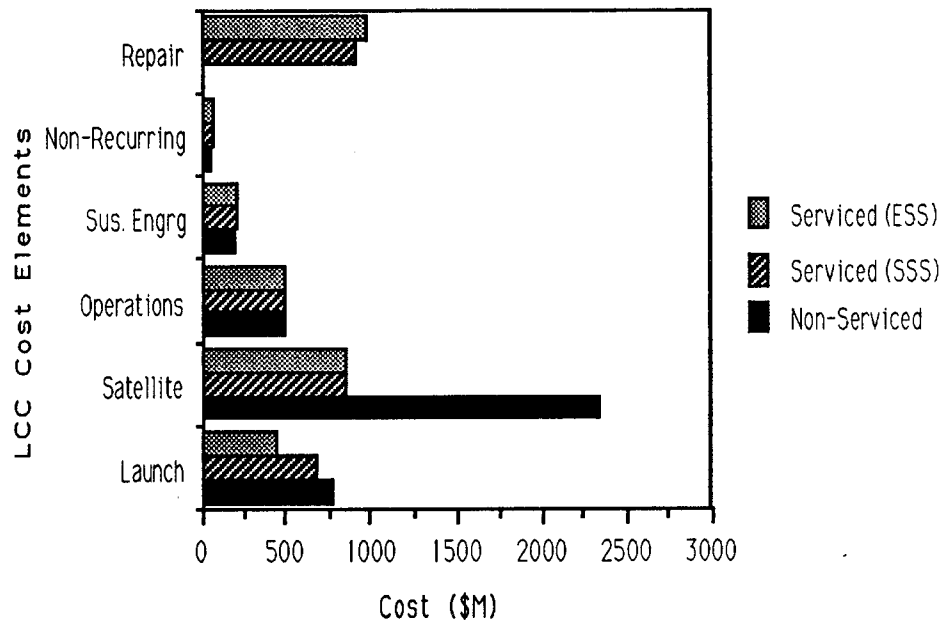
## **LIFE CYCLE COST COMPONENTS**

The facing chart graphically illustrates the breakdown of the LCC for each of the cases. The chart clearly shows that one of the principle reasons for the reduction in life cycle costs for the servicing cases over the non-servicing cases is the reduction in launch costs. The reason this occurs is that the repair mission launch mass is less than a replacement satellite cost. For the SSS case this translates into reduced shuttle launch charges. In the case of the ESS it allows the use of a less expensive launch vehicle.

The left chart shows some of the similar information shown on the right chart except that the repair kit (ORU + Servicer) costs have been added to the satellite cost. This graphically illustrates that the reduction in life cycle cost is due to a reduction in the satellite replacement costs (hardware) and the launch cost over the program.

# LIFE CYCLE COST COMPONENTS

SPACE SYSTEMS/ **LORAL**



## **AXAF PARAMETRICS**

Once a baseline set of results had been developed for all three cases, parametrics were run to determine the sensitivity of the results to the following parameters: Satellite cost, reliability, Servicer Cost, and Launch Cost.

The satellite cost parametric was to determine the effect of the original asset cost on the economic viability of servicing. In developing the parametric for this case, it was assumed that the satellite and replacement ORUs were affected by the same amount. The 25% variation was selected in order to provide a sufficient variation in the results to establish a pattern.

The reliability parametric was performed to investigate servicing strategies. The baseline spacecraft contained sufficient redundancy to provide a 5 year servicing interval. The satellite reliability levels were adjusted to model no redundancy and triple redundancy. In addition the spacecraft cost, mass and launch costs were adjusted accordingly.

The servicer cost parametric was included to determine the impact of servicer system cost on the results. Initially the cost of the SSS was decreased by \$5M and increased by \$25M. Correspondingly the ESS costs were decreased by \$5M and increased by \$30M.

The launch cost parametric was included to determine the impact launch charges have on the economic performance of servicing. The launch charges were varied by +/- 20% to establish a trend. It is important to note that launch cost increases were assumed to be identical for both the Shuttle and the ELVs.

These 4 parametrics cover the major factors that determine the life cycle cost.

## AXAF PARAMETRICS

SPACE SYSTEMS/ **LOREAL**

Case	Parametric 1 Satellite Cost				Parametric 2 Reliability*		Parametric 3 Servicer Cost		Parametric 4 Launch Cost	
	S/C		Rep Kit		Payld	Bus	Servicer		Rec. Cost	
	NR	R	NR	R	Ps	Ps	NR	R	Sat.	Svcr
Non-Serviced	±25%	±25%	N/A	N/A	0.85 0.88	0.66 0.99	N/A	N/A	±20%	N/A
SSS Servicing	±25%	±25%	±25%	±25%	0.85 0.88	0.66 0.99	N/A	-\$5M +\$25M	±20%	N/A
ESS Servicing	±25%	±25%	±25%	±25%	0.85 0.88	0.66 0.99	-\$5M +25M	-\$5M +\$30M	±20%	N/A

\* Satellite, repair kit and launch costs adjusted accordingly

### 5% DISCOUNTED LCC PARAMETRIC RESULTS

Case	Parametric 1			Parametric 2			Parametric 3			Parametric 4		
	Hi	Nominal	Lo	Hi	Nominal	Lo	Hi	Nominal	Lo	Hi	Nominal	Lo
Non-Serviced	2740	2364	1988	2371	2364	2500	N/A	2364	N/A	2459	2364	2268
SSS Serviced	2342	2039	1736	1944	2039	2092	2079	2039	2031	2126	2039	1952
ESS Serviced	2249	1938	1628	1937	1938	1938	2010	1938	1925	1998	1938	1877

## PARAMETRIC 1 RESULTS

The graph on the facing page illustrates the impact of satellite cost on the relative economic performance of the two servicing scenarios. The graph is plot of the spacecraft recurring cost versus the difference in the non-serviced and serviced LCC (ie. the life cycle cost savings due to servicing).

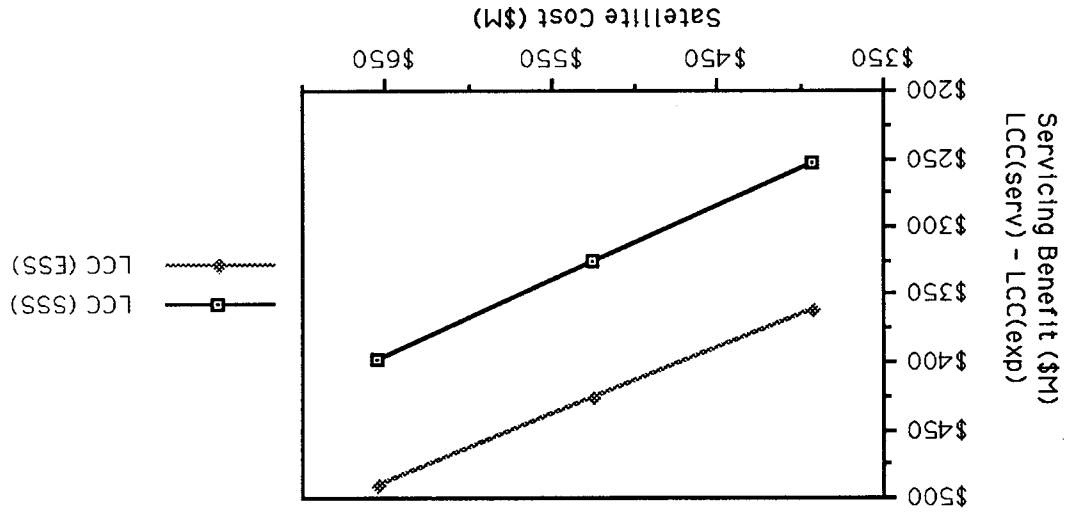
The plot shows that servicing is marginally cost effective for the Shuttle launched SSS mission for the nominal satellite cost (the mid point on the curve). For the nominal satellite cost the percentage of the life cycle cost savings is on the order of 14%, however, the standard deviation on the life cycle cost typically runs around 10%. This implies that given the uncertainty in the results, servicing may or may not be cost effective. The performance of the SSS scenario was independent of variation in satellite cost.

The results for the ESS indicate that servicing is definitely more cost effective. The reason for the improvement in performance is the use of a less expensive launch vehicle for the servicing missions. The percentage in LCC reduction is approximately 18% over the entire range of variation.

The results indicate that the relative benefit of servicing is independent of satellite cost. The reason for this is that when the satellite cost goes up, the cost of replacement components rises as well which causes the percentage of life cycle cost savings to be relatively constant with changing satellite cost.

# PARAMETRIC 1 RESULTS

SPACE SYSTEMS/ LORAL



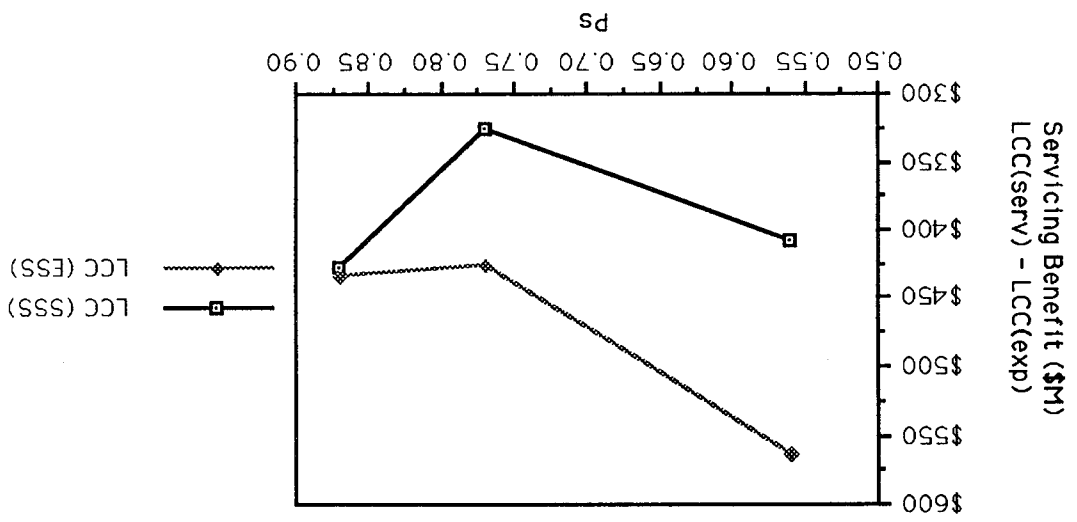
## PARAMETRIC 2 RESULTS

Parametric 2 involved varying the spacecraft reliability from no redundancy to triple redundancy. In most cases, the spacecraft bus included 2:1 redundancy, but the payload was mostly single string. Therefore, the reliability variation for the bus ranged from single-to-triple redundancy schemes, but the payload reliability was not significantly effected with a redundancy variation. This resulted in a Ps variation of 0.66 and 0.99 for the bus, and a 0.88 and 0.85 variation for the payload. As discussed earlier, the spacecraft mass, ORU mass, spacecraft cost, ORU cost and launch costs were adjusted accordingly. The curves illustrate the expected effect of reliability on the performance of servicing. That is, as redundancy decreases, the satellite cost and associated launch costs decreases. Also as redundancy and hence the reliability of the satellite decreases, the number of replacement satellites and/or servicing missions decreases. Since the servicing mission costs are less than the satellite replacement mission costs, servicing will be more cost effective for this case (the breakdown of servicing mission costs is shown in a later graph). The converse of this argument applies to the increased redundancy case by the same reasoning. Additional redundancy implies additional satellite and launch costs but fewer replacement missions. Since the servicing missions cost much less than the replacement missions servicing again more cost effective. The reason servicing appears to be less cost effective for this variation is that the number of servicing and/or replacement mission is decreased, and as the number of servicing mission drops the LCC tends toward the non-servicing life cycle cost.

An interesting result is that the most cost effective redundancy strategy is the baseline strategy (see parametric results table). This suggests that a unique combination of redundancy and servicing will provide the lowest overall life cycle cost.

# PARAMETRIC 2 RESULTS

SPACE SYSTEMS/ LORAL



## RELIABILITY PARAMETRIC INPUTS

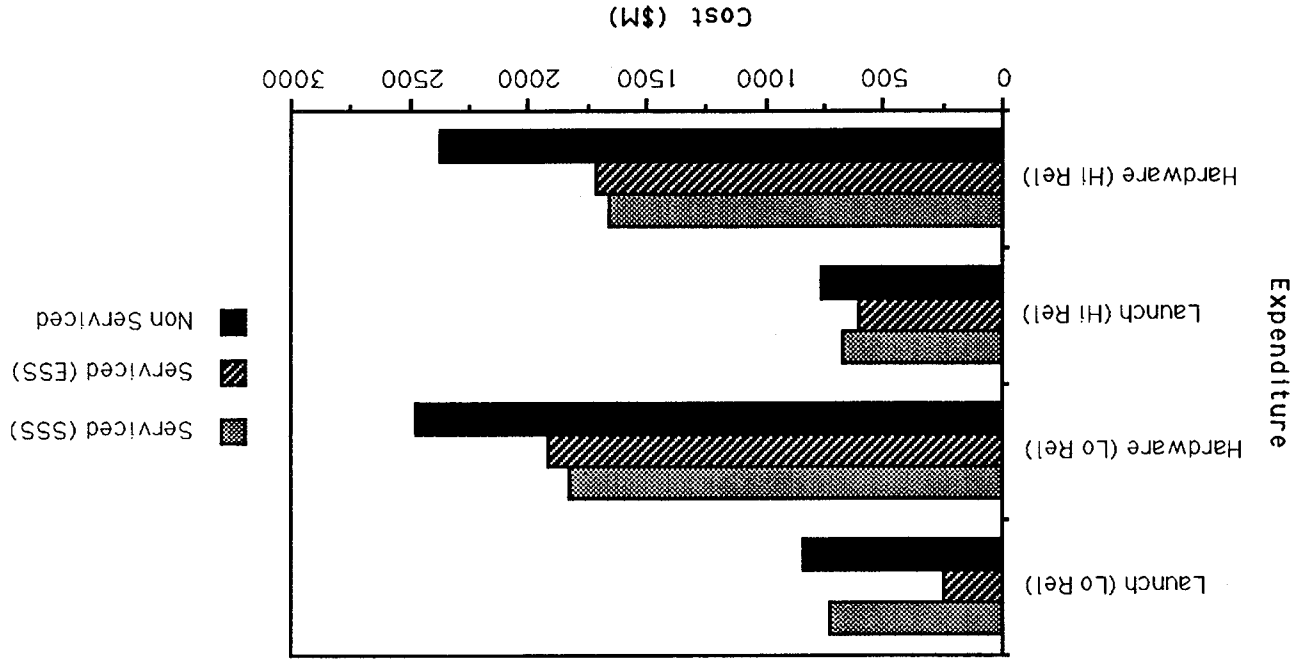
Case	Sensor Ps	Bus Ps	Satellite Cost (\$M)		ORU Cost (\$M)	Launch Cost (\$M)	
			Rec. Cost	Non-Rec Cost		Placement	Servicing
Non-Serviced	0.85	0.66	494.50	52.20	N/A	163.60	N/A
ESS Serviced	0.88	0.99	554.50	62.00	N/A	174.70	N/A
ESS Serviced	0.85	0.66	496.00	57.00	259.00	182.60	N/C
ESS Serviced	0.88	0.99	553.00	67.00	319.00	193.60	111.60
SSS Serviced	0.85	0.66	496.00	57.00	259.00	188.10	123.30
SSS Serviced	0.88	0.99	553.00	67.00	319.00	193.60	134.30

## **PARAMETRIC 2 RESULTS**

The preceding graph showed that both servicing scenarios offered the same performance in terms of LCC. The reason for this was that the increased redundancy caused a change in launch vehicles for the ESS case. The added mass due to the increased redundancy forced a change from the Delta II to an Atlas/Centaur. This dramatically increased the launch costs and diminished the benefit of the expendable servicer. This concept is illustrated graphically in the chart on the facing page. In this case the SSS actually would be the preferred choice, since it would probably have increased capability and reliability over a mission specific servicer.

# PARAMETRIC 2 RESULTS

SPACE SYSTEMS/ LORAL



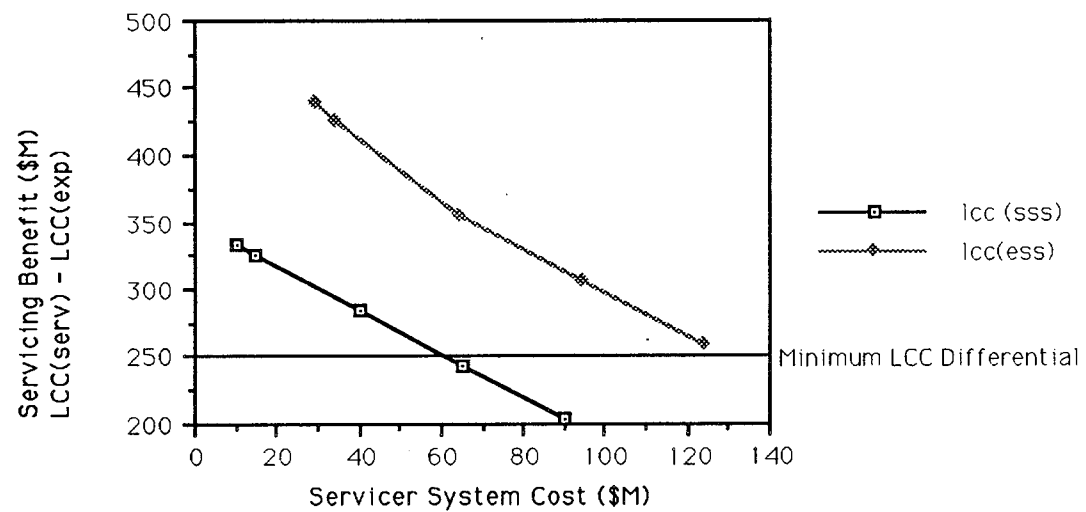
## PARAMETRIC 3 RESULTS

The graph on the facing page shows the impact of servicer cost on the economic performance of servicing for both the ESS and SSS servicing missions. In the case of the SSS mission, the servicer users fee was reduced by \$5M and increased by \$25M. For the ESS mission, the servicer cost was reduced by \$5M and increased by \$30M. Since the goal of this parametric was to establish what the users could afford to pay for servicing systems, it was decided to run additional cases where the servicer cost was tripled and quadrupled for both servicing systems.

The attached plot clearly shows that servicer system cost can be increased significantly before the benefit of servicing becomes questionable. The approximate standard deviation of the results has been drawn on the graph to illustrate the maximum costs of the servicing systems. Reading from the graph it can be seen that the maximum users fee for the SSS is about \$60M and the maximum servicer cost is approximately \$125M.

# PARAMETRIC 3 RESULTS

SPACE SYSTEMS/ **LORAL**

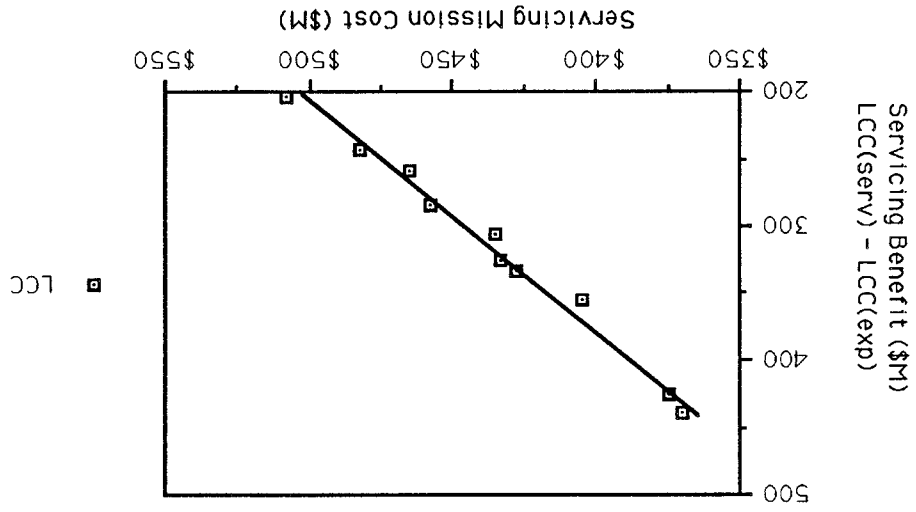


## IMPACT OF SERVICING ON MISSION COST

The primary difference in costs between the ESS and SSS servicing mission is the launch vehicle. Since the launch vehicle is major contributor to servicing mission cost, a second plot of the parametric 3 data is shown to illustrate the effect of servicing mission cost on the economic performance of servicing. The x axis of the plot is "Repair Mission Cost" which is composed of the ORU costs, the servicer cost and the servicing mission launch costs. The chart shows that the break even point for servicing is with a servicing mission cost of \$475M. This means that the sum of the three mission cost components must be less then or equal to \$475M for servicing to be economically viable.

# IMPACT OF SERVICING ON MISSION COST

SPACE SYSTEMS/ LORAL

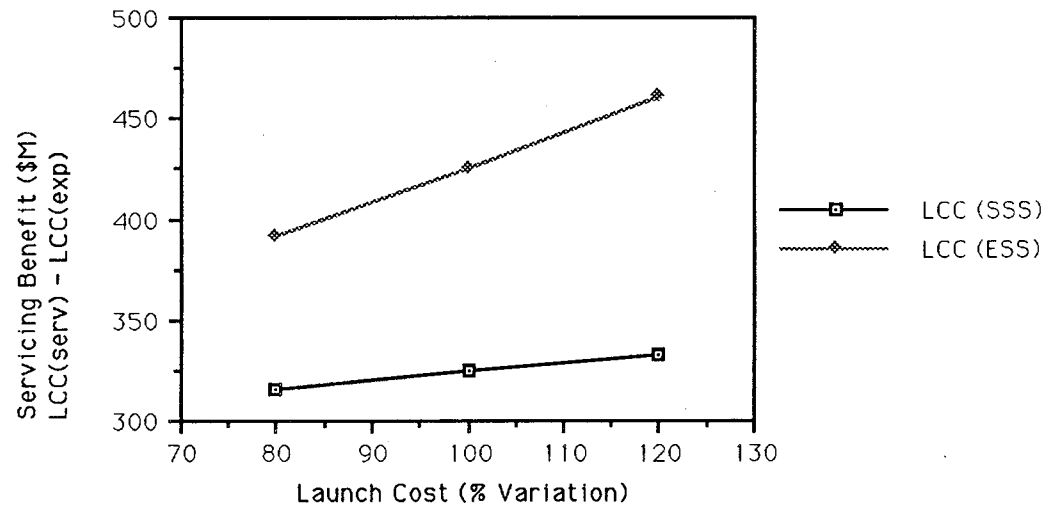


## PARAMETRIC 4 RESULTS

Parametric cases were run with +/- 20% variation in launch costs and the results are summarized in the graph on the facing page. The chart shows the general trend that as launch cost increase, servicing becomes more cost effective. This is again due to the fact that servicing requires that only a fraction of the total satellite mass be transported to orbit. The reason for the difference in slopes for the SSS and ESS cases is that the ESS allows the use of a lower cost launch vehicle.

# PARAMETRIC 4 RESULTS

SPACE SYSTEMS/ **LORAL**



## **AXAF SUMMARY**

The study examined many servicing options and compared the total LCC to a similar expendable spacecraft which are replaced rather than serviced. The study narrowed the option field down to ESS, SSS, and EVA based servicing options. It was determined that servicing through the space station resulted in higher cost, and the risk to the mission success was unduly jeopardized by the short window of opportunity, and the long waiting periods between successive servicing windows.

The three servicing options all proved to be cost effective over an expendable AXAF. The ESS costs were derived from an in-house preliminary study, as no funded ESS study currently exists. It is felt that the technology for a mission specific-simple ORU replacement robotic system will be available during the mission time frame. However, the costs were based upon the timely development of the SSS and OMV programs. Although the OMV funding has been eliminated, it is our opinion that a similar program with a limited scope should be initiated to fill the gap. We make this recommendation based on the potential LCC saving resulting from this study, and many other reputable studies.

# AXAF SUMMARY

SPACE SYSTEMS/ **LORAL** —

- The data indicates that an Expendable Servicer results in a potential LCC savings of 18% (\$426M) over an expendable AXAF
- The SSS option results in a potential LCC savings of 13.7% (\$325M) over an expendable AXAF
- The EVA option results in a potential LCC savings of 10.5% (\$248M) over an expendable AXAF
- Reliability has a major effect on the benefit of servicing; it effects both frequency and cost of servicing mission. The LCC cost results from a unique combination of redundancy and servicing.
- The parametric study has shown that if servicer costs are higher than the stated baseline, servicing could still remain cost effective. The exact value is dependant on the servicing scenario.
- The data supports the conclusion that SSF-based servicing is not cost effective.
  - The servicing window of opportunity from SSF is less than 3 weeks, with approx a 4 year waiting period before nodal alignment.
  - This severe constraint will result in longer lead time planning to ensure the window of opportunity is not missed, thus increasing servicing related costs.

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## POLAR ORBITING PLATFORM

## **INTRODUCTION: CURRENT POP ARCHITECTURE**

The current US Polar Orbiting Platform (POP) Program consists of three EOS-A platforms and three EOS-B platforms. These platforms have a 5 year mission life to provide continuous Earth observations for 15 years. EOS-A series of platforms will support a payload of 3,000-3,500 kg, and provide 6 kW total power output. The design life of each platform is limited by the expected lifetime of the Earth observation sensors. EOS-A platforms are scheduled for replacement at 5 year intervals, but are being designed for servicing if an effective means becomes available during the life of the mission. EOS-B platforms are envisioned to be similar in design to the EOS-A platforms, but with a modified payload complement. It is the objective of the Satellite Servicing Economic Study to model, as close as possible, the current POP architecture, and to investigate servicing options that would directly compare with a replacement platform strategy.

# INTRODUCTION: CURRENT POP ARCHITECTURE

SPACE SYSTEMS/ **LORAL** —

## POP current system architecture

### Eos-A:

- Current baseline of 3 platforms each with a 5 year design life, located in a 705 km, sun-synchronous 1:30 pm nodal crossing time.
- Payload mass of 3,000 kg
- 6 kW average platform power, 3.2 kW for the payload
- The baseline architecture calls for replacement of the platform after 5 years. However, the platform ORUs are designed to be serviced, if an effective means of on-orbit servicing becomes available

### Eos-B

- 3 platforms similar to Eos-A with expanded science capabilities to monitor global change

## **APPROACH: SSES IMPLEMENTATION**

The approach is to investigate the expendable and serviceable alternatives for EOS-A Platforms. No attempt has been made to evaluate EOS-B platforms due to the limited data available. It was also assumed that the cost trends generated for EOS-A platforms would be representative for EOS-B as well.

One expendable scenario and two serviceable scenarios are presented in this study. Many architecture studies have been performed (see references) in the past to evaluate the benefits of various servicing options. The two most recommended servicing options were chosen for the baseline servicing options in this study: The Add-On Active Carrier; and the Active Carrier with robotic exchange capabilities. It was assumed that each of these servicing options have the capability to rendezvous and dock with the POP. In other words, the POP will not be required to de-orbit for servicing.

The Atlas II launch vehicle was selected over the Delta II launch vehicle to carry the servicer to orbit. The decision was based on the recommendations of the Hixson Report, May 1990. This study did not undertake a packaging analysis and trade study to justify this selection. The Hixson Report found that the Atlas II could provide a much higher percentage of serviceable payload than the Delta II.

The payload servicing strategy assumed the "replace at design life" method. All science instruments were assumed to have a 5 year design life with a probability of success of 0.85. If however, the model triggers either a launch or on-orbit spacecraft failure, a replacement platform or servicing mission is initiated.

# APPROACH: SSES IMPLEMENTATION

SPACE SYSTEMS/ **LORAL** —

- The POP-SSES will investigate serviceable and expendable cases of the Eos-A platform series. No attempt has been made to cost the Eos-B platform system.
- Each scenario has been defined using available data, and by assumptions when data was not available.

<b>MISSION events</b>	<b>Earth observation of global change</b>
<b>ORBIT</b>	<b>705 km, sun synchronous, 1:30 pm nodal crossing time.</b>
<b>LAUNCH VEHICLE</b>	<b>Titan IV Initial Placement Atlas II Servicing</b>
<b>MISSION LIFETIME</b>	<b>Total: 20 years On-orbit: 15 years</b>
<b>PLATFORM R COST</b>	<b>\$700M</b>
<b>SERVICING OPTIONS</b>	<b>1. Active Add-on Carrier 2. Active Carrier with Robotic Exchange System</b>

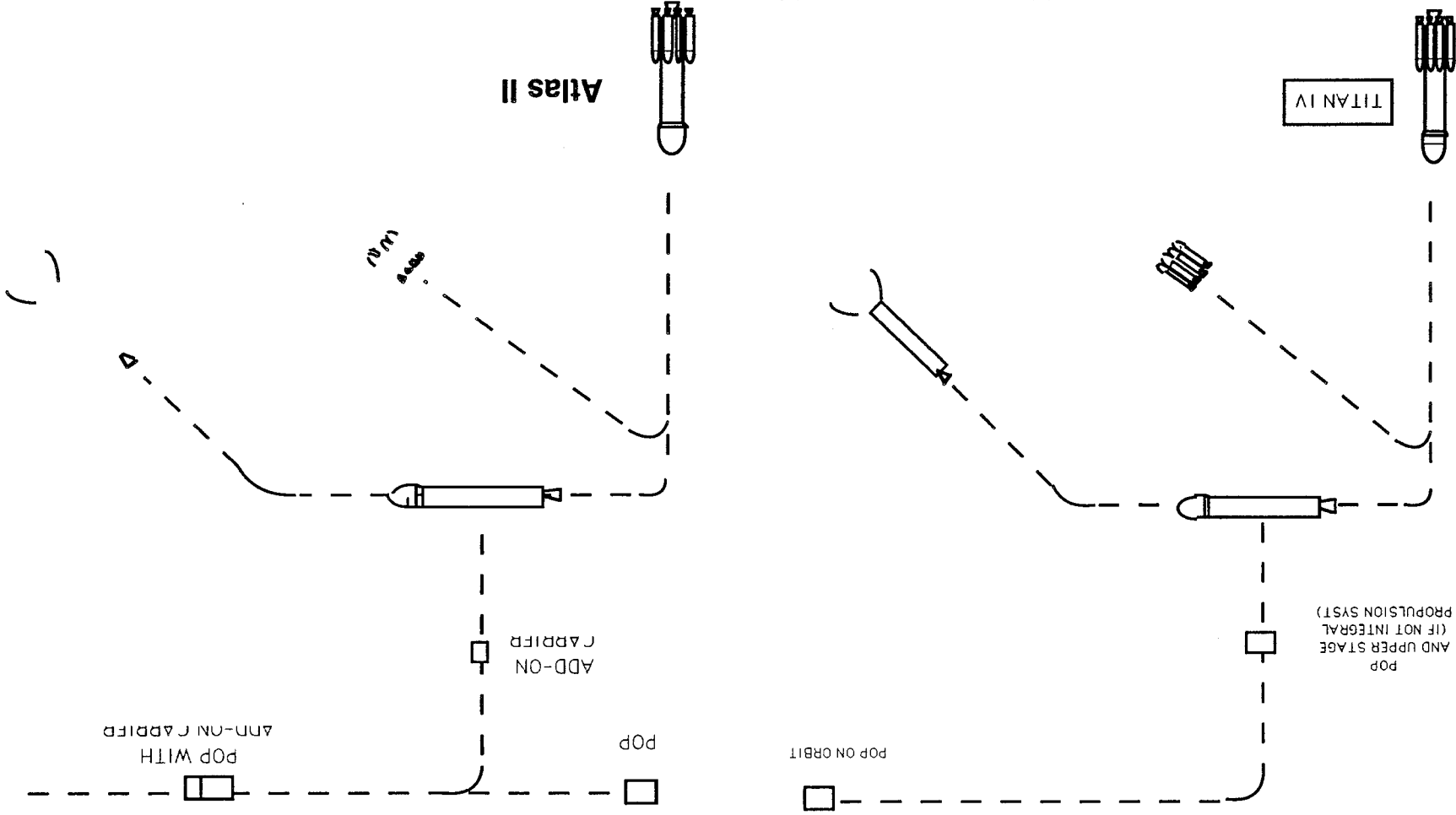
## **ADD-ON CARRIER PLATFORM SCENARIO**

The diagram below illustrates the major event sequence of initial placement and servicing of the POP using an Add-on carrier methodology. The initial placement is identical for all POP scenarios examined in this study. The expendable platform scenario, which is used to evaluate the cost effectiveness of a servicing option, utilizes the initial placement scenario each time a satellite failure occurs. As can be seen, this will provide a direct comparison between the cost of a servicing mission relative to the cost of replacement.

The Add-On Carrier Serviceable option consists of one platform bus designed for a 15 year mission life. The expected wear out of the sensors is 5 years, therefore, nominal servicing missions are scheduled for year 5 and year 10. The Titan IV launch vehicle is assumed for initial launch and placement of the platform, and the Atlas II series launch vehicle is assumed for the launch of the active carrier servicing vehicles. The Atlas was the recommended servicer launch vehicle, as mentioned previously, to maximize the percentage of science payload serviced.

# ADD-ON CARRIER PLATFORM SCENARIO

SPACE SYSTEMS/ LORAL

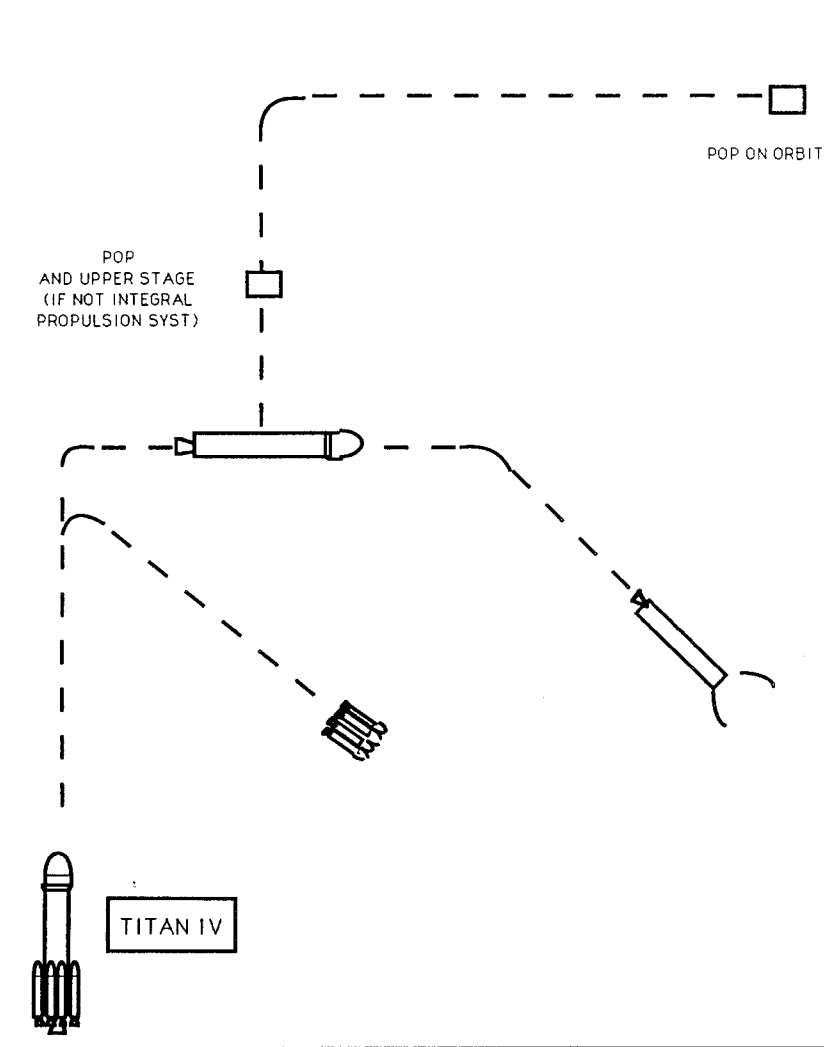


## **ACTIVE CARRIER ROBOTIC EXCHANGE SCENARIO**

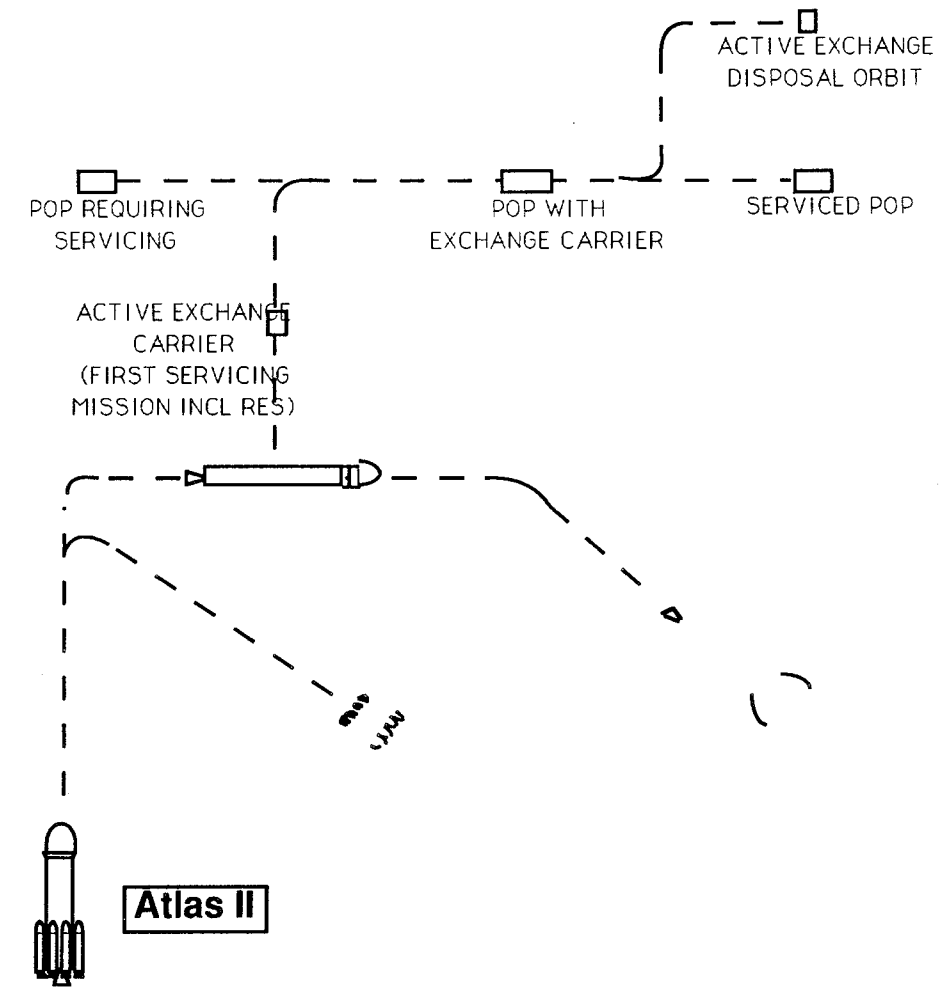
The robotic exchange servicing option uses a similar active carrier vehicle as the Add-On carrier. The design is not subject to the same thermal compatibility requirements as the Add-on carrier, and more ports are available for instrument mounting because the instruments are not required to be in their on-orbit configuration during carrier transfer. The robotic exchange system is a reuseable system that integrated onto the active carrier and transported to the platform on the first servicing mission. The robotic exchange system remains permanently on the platform for future servicing missions.

# ACTIVE CARRIER ROBOTIC EXCHANGE SCENARIO

SPACE SYSTEMS/ **LORAL**



INITIAL PLACEMENT



SERVICING MISSION

## GENERAL POP ASSUMPTIONS

Servicing of the platform is limited to expendable launch vehicles, as no capability exists for Shuttle launches to near-polar orbits.

The Titan IV launch vehicle is assumed for initial launch and placement of the platform, and the Atlas II series launch vehicle is assumed for the launch of the servicing missions. The Atlas was the recommended servicing launch vehicle, as mentioned previously, to maximize the percentage of science payload serviced.

The ideal method of treating failures would have been to ascertain accurate POP reliability and planning data, and to translate this data into a strategy consistent with model inputs, that would trigger a servicing mission when a specific threshold was reached. This threshold could either be defined as a specific sensor failure, a combination of sensor failures, or a bus failure. Two problems prevented this approach from being implemented; An existing strategy with consistent probable failure data, and a SATCAV model limitation. Although some probability of failure data was available in the D. Hixson report (POP Servicing Study, Final Report, May 7, 1990), no strategy for specifying what series or combinations of failures should trigger a servicing mission.

The model was originally designed for identical servicing missions, and therefore, is not capable (without model modifications not funded in this study) of triggering servicing missions specific to different sensor failures. Since the maximum expected lifetime of the sensors was 5 years, the servicing mission was designed for that specific servicing scenario. An overall system reliability number of .75 P(s) at 7.5 years, specified by Chris Scolese, Eos Project Office at GSFC, was used.

# GENERAL POP ASSUMPTIONS

SPACE SYSTEMS/ **LORAL** —

- No STS servicing capability to polar orbit
- Atlas II launch vehicle assumed for servicing missions
- 5 year engineering development period
- System level reliability of .75 @ 7.5 years was assumed
  - science payload: 0.85
  - Platform bus: 0.88
- The repair mission assumed a 5 year expected lifetime for all science instruments. If a failure occurred prior to the 5 year intervals, the model would initiate a repair mission.
- The SATCAV model is designed for only one definition of the repair mission. The SATCAV model servicing criteria will initiate a repair mission when a specific combination of system failures occur. However, we were not able to ascertain a servicing strategy which prioritized sensors to determine what combination of failures can be allowed before a servicing mission is initiated. Therefore, system level reliability was assumed.

## POP BASELINE INPUT COSTS TO SATCAV MODEL

The baseline costs for the POP scenarios are shown below. Most of the cost data has been extracted from the Hixson report (May, 1990), and some modifications were made with input from Chris Scolese, GSFC.

When a failure occurs, either total platform replacement or a repair mission is initiated. Total replacement is always assumed in the expendable scenario, and only assumed for the serviceable scenarios if the platform can not be serviced. A 90% repairability factor is assumed to account for the probability that the platform can not be serviced. The repair mission consists of a servicer and launch vehicle. Since the model is restricted to identical repair mission costs, and a total of 3 servicers are required to replace the entire payload complement, a complete servicing mission must include three launches and three servicers to replace the entire payload. To account for the reliability effects of 3 servicing launches per servicing mission, the launch vehicle reliability was adjusted from .98, as agreed in the mid-term report, to 0.94.

Instrument and platform spares are not input into the model. The method by which the model accounts for the cost of spares is when a failure triggers a replacement or repair mission to meet the mission lifetime.

The baseline costs for the Add-On carrier serviceable option were increased over the expendable case to allow for the added development and hardware modification costs. GE Astro Space has concluded that 2 Add-On carriers could be accommodated by the existing platforms without significant design modifications.

Previous packaging studies discussed in the Hixson Report have concluded that 3 Add-On carriers would be necessary to replace the entire POP instrument payload. As a result of the additional design analysis and hardware modifications necessary to support at least 3 Add-On carriers, the NR cost of the platform for the Add-On scenario was increased by 50% and the recurring cost by 10% over the expendable platform.

The baseline costs for the Active Carrier, Robotic Exchange serviceable option were increased over the expendable case to allow for the added development and hardware modification costs to incorporate the robotic system. Although the current platform design is being designed for servicing, it was not known whether that includes the necessary scarring to accommodate the Robotic Exchange System (RES). Therefore, the NR cost of the platform was increased by 20%, and the recurring cost by 10%. Platform integration costs for both of the serviceable options were assumed to be 20% higher than the expendable platform.

Since the recurring cost of the Robotic Exchange System and the cost of Robot-to-platform integration is a one time cost, the model treated this as a nonrecurring cost input.

The WTR pad modification was a point of some controversy. The \$500M was verified by D. Hixson and included in the POP Servicing Study Final Report. It was however, a questionable line item according C. Scolese, GSFC. The question still remains unanswered whether the POP program would bear the total cost of such a modification in the year 2000 time frame. An in-house decision was made to implement the full \$500M in the baseline scenario, but show in the parametrics, the scenario without the charge.

# POP BASELINE INPUT COSTS TO SATCAV MODEL

SPACE SYSTEMS/ **LORAL**

	Expendable		Add-On		Robotic Exch	
	NR	R	NR	R	NR	R
	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)
<b><u>Initial Placement</u></b>						
Platform	241	237	361.5	260	289.2	260
Instrument set	579	300	579	300	579	300
Platform Integration		62		74.4		74.4
Payload Integration		100		100		100
<b><i>Total Replacement Hardware Cost</i></b>		<u>699</u>		<u>734.4</u>		<u>734.4</u>
<b><u>Servicer</u></b>						
Active Carrier Servicer			50	31	50	31
Serviceable Inst. set				100		100
ORU's				50		50
PL Integration				20		20
Platform Systems				23		23
Robotic Each Syst					100	30
Robot Integration						12.8
WTR Pad Modifications			500		500	
<b><i>Total Servicer Hardware Cost</i></b>		<u>0.0</u>		<u>224.0</u>		<u>266.8</u>

## **POP RESULTS COST SUMMARY**

The results of each the POP scenarios are summarized below. The results indicate that servicing does not appear cost effective given the assumptions and baseline input costs. The total discounted LCC of the Expendable scenario is \$3652M in FY89 dollars. The nearest serviceable option is \$4342M, an increase of \$690M. The differences in the total discounted LCC between the two serviceable scenarios (Add-on carrier and Robotic Exchange carrier) are small, approximately 1.6%.

The output data indicate that 4.6 platforms are required for the expendable scenario, and that 1.5 platforms/3.1 servicing missions are required to maximize the overall availability over the 15 year mission lifetime. The interpretation of the number of platform or servicing mission, as shown below, is the modelling implementation of spreading the costs of a new platform or servicers. No modelling techniques are incorporated to stop the implementation of a new platform or servicer near end-of-life if a failure occurs. If a failure does occur near the end of the mission lifetime, then a percentage of the replacement cost is spread over the remaining mission years.

The LCC costs spans a 20 year program time frame; 5 years of development, and 15 years of active on-orbit performance. If a failure occurred during launch, a new platform was launched. If a payload or platform failure occurred, a servicing mission would be attempted in order to maintain system availability for the full 15 year mission life. The serviceable platform assumed a 90% factor for a successful servicing mission. No degradation of that factor was assumed after a successful servicing mission. If the platform could not be serviced, then a new platform would be launched.

The serviceable scenarios have included a one time nonrecurring cost of \$500M to modify the WTR for Atlas launch capability. The possible exclusion of this line item has been examined in the parametric analysis. When this NR WTR cost is removed the total discounted LCC difference between all three cases is approximately \$260M, or 6.8%.

# POP RESULTS COST SUMMARY

SPACE SYSTEMS/ **LORAL** —

	<u>INPUT DATA</u>				<u>OUTPUT DATA</u>		
	Satellite Cost (\$M)	Sat Launch Cost (\$M)	Servicing Mission Cost (\$M)	Servicing Mission Launch Costs (\$M)	LCC (\$M)	# SAT	# Servicing Mission
POP 1 (Exp)	699	250	N/A	N/A	3652	4.3	0
POP 2 (Add-On Carrier)	735	250	224	75	4342	1.5	3.2
POP 3 (Active Carrier Robotic Exchange)	735	250	267	75	4412	1.5	3.1

- **3 servicing missions are necessary to replace the entire instrument set**
- **Expendable platform is the most cost effective solution**
- **Add-On Carrier and Robotic Exchange Carrier are within 2% of each other. Too close for a meaningful conclusion.**
- **If the WTR NR cost is removed from the POP 2 and POP 3, then all three scenarios are within 8%, which is below the 10% confidence threshold defined at the beginning of the study.**

## LIFE CYCLE COST COMPONENTS

The bar graphs below depict the undiscounted components of the the total LCC for each of the POP scenarios. Two graphical representations are shown so that a comparison can be made between the platform and repair mission costs individually, and combined. As would be expected, the platform cost for the expendable scenario is much higher than the servicing scenarios. However, when the total cost of the combined platform and repair mission costs are examined, it shows that an efficient servicing strategy has not been realized.

There are three main contributors which undermine the cost effectiveness of the POP servicing scenarios. The first, is that the cost to repair the platform is just as expensive as to replace it. The second, is that three Atlas launch vehicles, which are required to replace the payload complement, is on the same order as a single Titan IV platform launch. Thirdly, the \$500M NR cost to upgrade the WTR for Atlas launches.

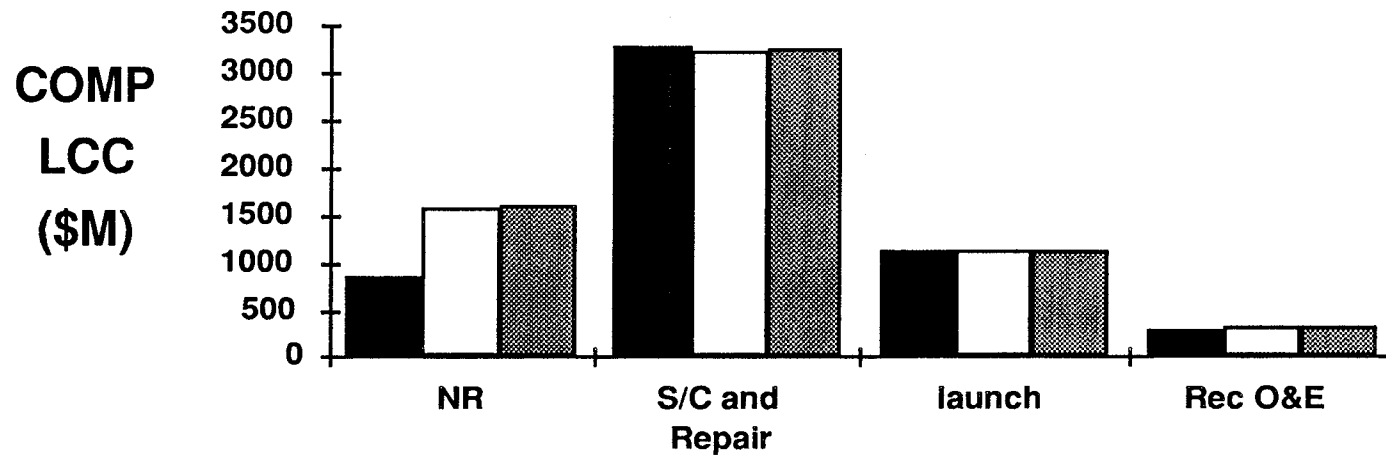
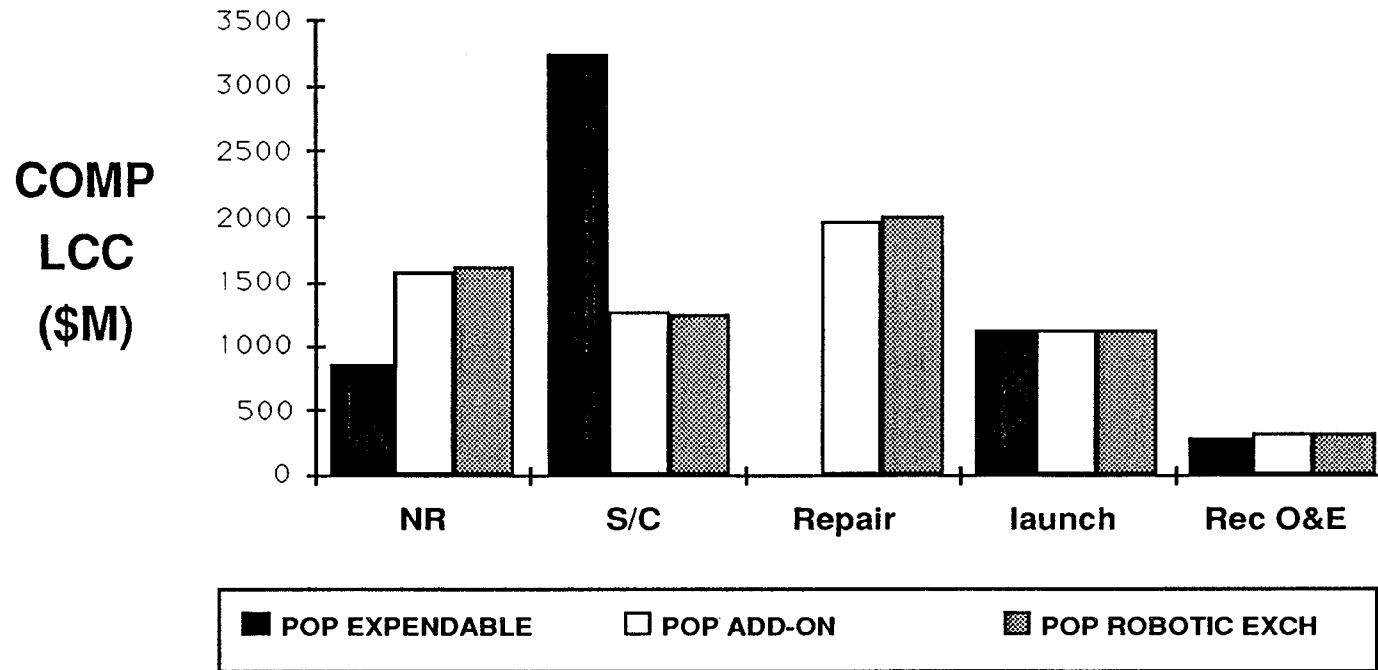
All of these major factors have a common source. The requirement to replace the entire payload set at the expected lifetime of 5 years. If this is truly an uncompromising requirement, and the reliability estimate is representative, then the stated conclusion that platform replacement is the most cost effective solution is reasonable. However, one might argue that servicing mission costs could be decreased significantly if the servicing strategy could be altered. For example, if the availability requirement could be backed off so that servicing missions could be scheduled based on impending failure analysis, and be prioritized by instrument, then the 3.2 servicing missions called out in the model could be reduced.

To examine this further, two potential analysis techniques could be initiated. The first, would involve a more detailed instrument reliability analysis, probably in a parametric fashion unless the stated failure modes and failure probabilities are well understood. This would be combined with a couple of prioritized servicing strategies that would map out a solution path for the SATCAV model to follow in order to identify when a servicing mission should be initiated. The result would be a more quantitative relationship between actual servicing mission costs and system availability.

The second technique to examine the impact of servicing costs on the LCC benefits is to assume that only two launches are required to service the platform at the expected lifetime. Although this is a very simplistic methodology, and cannot be directly related to the effect on system availability, it still provides a reasonable basis for the potential benefits of more detailed analysis. It is not within the scope of the current study to perform the detailed analysis. Therefore, the simplistic approach will be examined in the context of the parametric analysis to follow.

# LIFE CYCLE COST COMPONENTS

SPACE SYSTEMS/ **LORAL**



## **POP PARAMETRIC ANALYSIS INPUTS**

The following chart shows the 4 parametric studies for the Expendable, and Active Carrier Robotic Exchange mission scenarios. The Add-On carrier was not included in the parametrics because the baseline results were a were very close to the Robotic Exchange mission, and that It was felt that the one case would adequately indicate the cost savings trends of servicing versus replacement platforms.

The \$500M WTR pad modification costs of have not been included in the following parametrics. It was mentioned earlier in the text, that it was not clear from the available information whether this represented actual cost to modify the WTR for Atlas launches. or, if the POP program would be charged the entire cost of such a modification. The decision was made to include the cost in the baseline analysis, but to eliminate it from the parametric analysis.

# POP PARAMETRIC ANALYSIS INPUTS

SPACE SYSTEMS/ **LORAL** —

PARAMETRIC CASES	PARAMETRIC 1 SATELLITE COST				PARAMETRIC 2 RELIABILITY		PARAMETRIC 3 SERVICER SYS. COST				PARAMETRIC 4 LAUNCH COST		
	PAYLOAD		REPAIR KIT		SENSOR	BUS	SERV KIT		Servicer Launch Cost		NR	RECURRING	
	NR	R	NR	R	MTTF	MTTF	NR	R	NR	R	NR	Initial	Servicer
POP A (Expendable)	±25%	±25%	-----	-----	80.8/10.4 PL cost Rec ±35% PL cost NR ±10%		-----	-----	-----	-----	-----	±20%	
POP C (Robotic Exch)	±25%	±25%	±25%	±25%	PL cost Rec ±35% PL cost NR ±10% Repair Kit Rec ±30%		Serv. Min -25% 386 Rob.Ex Max -25% 467			Min 136 Max 165		±20%	±20%

## POP SERVICING MISSION COST PARAMETRIC

The graph on the facing page illustrates the impact of repair cost on the relative economic benefits of servicing. The differential LCC is the difference between the indicated servicing option versus a corresponding expendable spacecraft. When the differential LCC is below zero, it indicates that a non-serviced, replacement spacecraft scenario is the most cost effective.

The plot shows that if servicing the entire payload is required, then the platform replacement is more cost effective. The baseline servicing kit cost for 3 servicing missions is \$626M, and the replacement cost for the Expendable and Robotic Exchange option is \$699M and \$735M, respectively. In addition, the launch costs for a servicing mission (3 Atlas launch vehicles) is estimated at \$225M, versus the replacement platform launch costs of \$250M (Titan IV). Clearly, these numbers do not give the servicing option much chance of being cost effective.

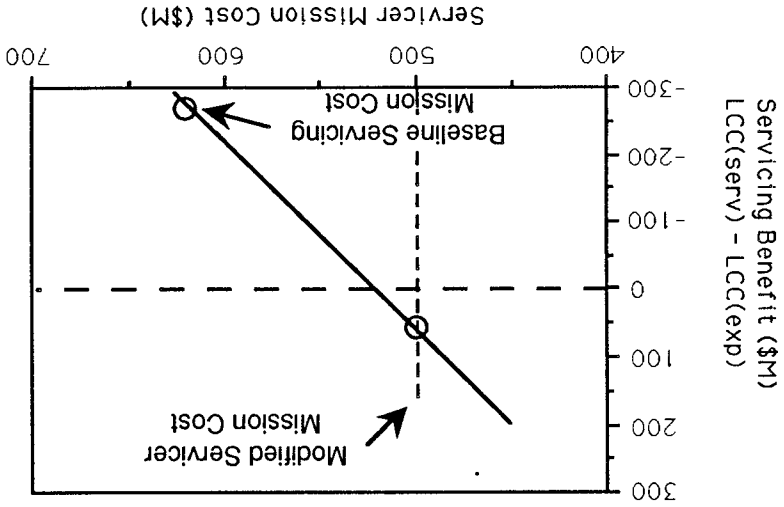
To obtain some useful comparisons with the following parametrics, a modified servicing mission has been defined. The rationale was to reduce the number of servicers required per servicing mission. This was accomplished by assuming only 2 Atlas launched servicers would be required per servicing mission. This will reduce the total payload replaced, but it will also show the the potential benefits that servicing can produce. The following modifications were assumed.

- \$240M payload replaced
- \$100M ORUs
- \$40M Payload integration
- \$60M Active Carriers
- \$30M Robotic Exchange System
- \$20M Platform Systems
- \$10M Robotic Integration

The following parametric charts will show the potential servicing benefits of both the baseline and modified repair kits.

# POP SERVICER KIT COST PARAMETRIC

— SPACE SYSTEMS/ **LOREAL** —



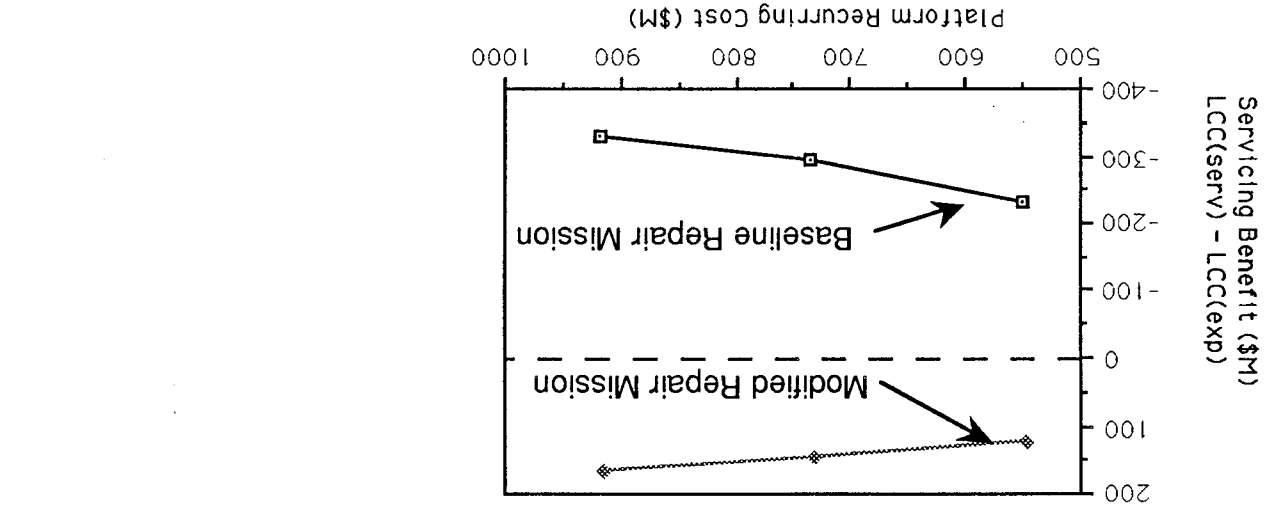
- This chart shows the potential benefits that servicing can achieve as a function of the servicing mission cost.
- The Baseline servicing mission which consists of 3 Atlas launches for replacing the entire payload is not cost effective as defined (ie. \$626M).
- A modified servicer mission which consists of only 2 Atlas launches indicates a potential \$150M LCC savings. This however, does not replace all of the science payload.
- Further benefits can be achieved if Servicer or ORU costs can be reduced.

## POP SPACECRAFT COST PARAMETRIC

The graph on the facing page illustrates the impact of satellite cost on the relative economic benefits of servicing. The differential LCC is the difference between the indicated servicing option versus a corresponding expendable spacecraft. When the differential LCC is below zero, it indicates that a non-serviced, replacement spacecraft scenario is the most cost effective.

This parametric was generated by varying the NR and R cost for both the platform and servicing mission. The plot shows that servicing is not cost effective for the baseline servicing mission when full payload replacement is required, even with a 20% reduction in spacecraft and servicing mission costs. Servicing becomes cost effective for the modified repair mission. The trend for the modified repair mission increases slightly with increasing satellite cost. The trend for the baseline data decreases with increasing spacecraft costs due to the high relative cost of the servicer mission.

# POP SPACECRAFT COST PARAMETRIC



- This chart shows the sensitivity of LCC savings for the servicing over expendable mission as a function of the platform recurring cost. NR and R costs were varied for both the platform and servicing mission.
- The Baseline data trend indicates that as platform costs increase, the benefit of the serviced platform decreases. This is true only because there is a small difference between platform and servicing costs.
- The Modified Repair Mission data trend indicates just the opposite, because the the repair mission cost is now substantially lower than the platform cost. So as platform cost increases, repairing the spacecraft becomes more cost effective.

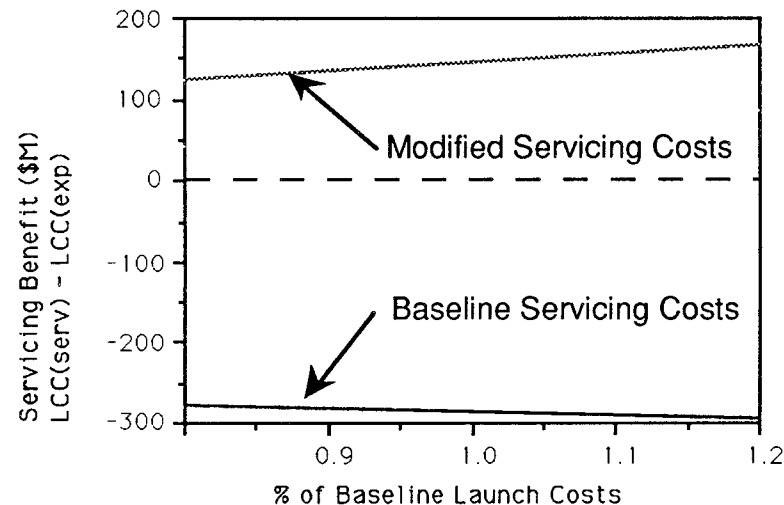
## POP LAUNCH COST PARAMETRIC

The graph on the facing page illustrates the impact of launch cost variation on the relative economic benefits of servicing. The differential LCC is the difference between the indicated servicing option versus a corresponding expendable spacecraft. When the differential LCC is below zero, it indicates that a non-serviced, replacement spacecraft scenario is the most cost effective.

The launch costs were varied by +20% relative to the baseline launch costs. The plots show a relatively flat response in LCC savings for a serviceable option. The modified servicing mission curve increases with increasing launch costs. This means that as launch costs increase, the platform replacement costs increase more than servicing costs and therefore, an increase in LCC savings due to servicing results. The opposite trend for the baseline data indicates that servicing mission and associated launch costs are greater than replacement costs, and therefore, the LCC savings due to servicing decreases as launch costs increase.

# POP LAUNCH COST PARAMETRIC

SPACE SYSTEMS/ **LORAL** —



- This chart shows the sensitivity of LCC savings of the servicing over expendable mission, as a function of the launch cost.
- The Modified Repair mission data trend indicates that as launch costs increase by a fixed percentage for both servicing and replacement, the benefit of servicing increases. This is simply due to the fact that platform launch costs are greater than servicing launch costs.
- The Baseline servicing trend indicates that as launch cost increases, the benefit of servicing decreases. This is true because the servicing mission launch costs are slightly higher than the expendable launch costs.

## POP SUMMARY

The results indicate that servicing is not cost effective given the assumptions and baseline input costs. The total discounted LCC of the Expendable scenario is \$3652M in FY89 dollars. The nearest serviceable option is \$4342M, an increase of \$690M. The differences in the total discounted LCC between the two serviceable scenarios (Add-on carrier and Robotic Exchange carrier) are small, approximately 1.6%.

There are three main contributors which undermine the cost effectiveness of POP servicing scenarios. The first, is that the cost to repair the platform is just as expensive as to replace it. The second, is that the costs of three Atlas launch vehicles, which are required to completely replace the payload complement, is on the same order as the cost of a single Titan IV platform launch, and thirdly, the \$500M NR cost to upgrade the WTR for Atlas launches.

The parametrics shows that servicing becomes cost effective when the servicing ground rules are changed. First, the \$500M WTR pad modification costs were not included in the parametrics. Then, a change in the servicing mission reduced the number of servicers required per servicing mission. This was accomplished by assuming only 2 Atlas launch vehicles and servicers would be required per servicing mission. This will reduce the total payload replaced, but it will also show the the potential benefits that servicing can produce. Although this is a very simplistic methodology, and cannot be directly related to the effect on system availability, it still provides a reasonable basis to understand when servicing POP becomes cost effective.

# POP SUMMARY

SPACE SYSTEMS/ **LORAL** —

- The Baseline results found that if total payload replacement is a requirement, then platform replacement is more cost effective than servicing.
- In order to replace the entire payload set, three servicers and launch vehicles are required. This drove the servicing mission costs to the same order as the platform replacement costs.
- The Add-on carrier and Robotic Exchange servicing scenarios were very close in total LCC. However, the number of Add-on carriers required for complete payload replacement cannot be accommodated by the existing platform design.
- The parametric study showed that:
  - The trend of launch, servicing mission, and platform replacement costs were highly dependant on the ratio of the servicing to platform replacement cost.
  - Servicing the POP could be cost effective if servicing mission costs were reduced.

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# EXPLORER PLATFORM

## **EXPLORER PLATFORM CURRENT SYSTEM ARCHITECTURE**

The current Explorer Program consists of the Multi-mission Modular Spacecraft and a platform equipment deck (PED) to support various science payloads. The MMS supplies the entire Explorer Platform (EP) with power, attitude control, communications and data handling. Mission specific support equipment can be mounted into available PED modules.

The First EP mission will support the Extreme Ultraviolet Explorer (EUVE) which will be launched by a Delta II launch vehicle. After completion of its mission (approximately 3.5 years), a second payload such as the X-Ray Timing Experiment (XTE) will be launched by the STS. The Explorer satellite will be retrieved, and the EUVE payload will be exchanged on-orbit with the new science payload.

It is the objective of the SSES to model the current EP architecture and to compare the servicing strategy with an expendable platform and other servicing options.

# **EXPLORER PLATFORM CURRENT SYSTEM ARCHITECTURE**

---

SPACE SYSTEMS/ **LORAL** —

- The MMS forms the core spacecraft for the Explorer Platform with a design life of 10 years
- The payload equipment deck is a modular equipment rack to accommodate mission specific support systems not provided by the 3 MMS subsystem modules (MEPS, MACS, and C&DH)
- Initial launch of the EP is on a Delta II with the EUVE payload
- The mission life of the EUVE is approx 3.5 years with no required servicing
- A Shuttle based servicing mission will be performed to remove the EUVE payload and install a second experiment (possibly XTE)
- A third experiment to utilize the full 10 year MMS design life has not been identified

## **APPROACH: SSES IMPLEMENTATION**

The approach is to investigate and compare the economic benefits of expendable and serviceable alternatives for the EP. One expendable and four serviceable scenarios are presented. Each option assumes initial launch of the EP in a Delta II launch vehicle with the EUVE payload. Then, whether or not the scenario is expendable or serviceable a replacement payload like the XTE is assumed. The STS serviceable options include, Shuttle retrieval of the EP at 330 nmi, Shuttle launch to 160 nmi and OMV retrieval, and Shuttle to SSF where the new payload is integrated to the OMV. The last servicing option utilizes the Expendable Servicing System (ESS) launched on an expendable launch vehicle.

# APPROACH: SSES IMPLEMENTATION

SPACE SYSTEMS/ **LORAL** —

- The approach is to investigate STS and expendable servicing options for the EP and compare with individual and expendable platforms.

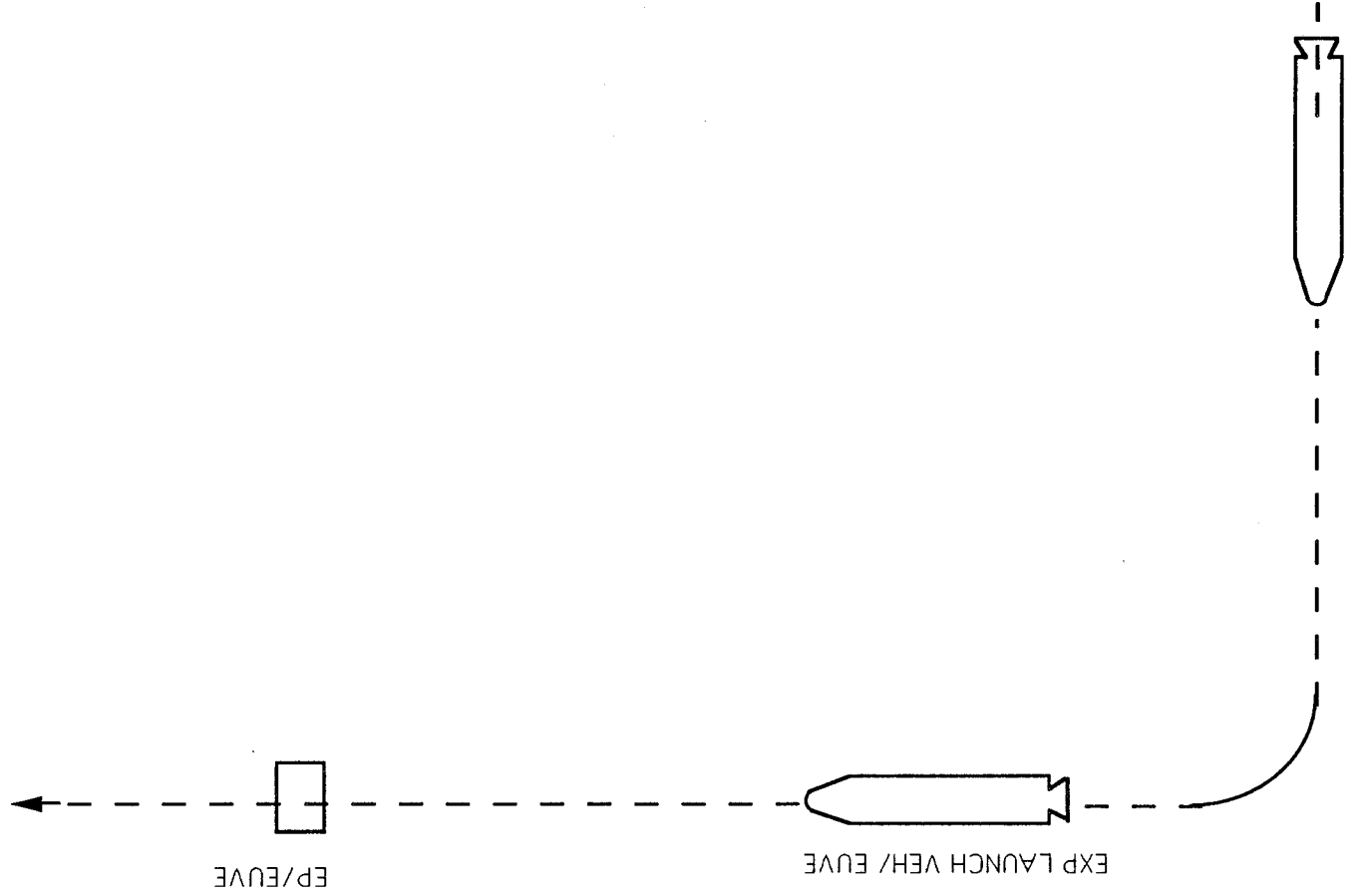
MISSION	Science, Astrophysics
ORBIT	330 nmi, 28.5° inclined, nominal
LAUNCH VEHICLE	Delta II Initial Placement STS, Delta II Servicing
MISSION LIFETIME	Total: 11 years On-orbit: 7 years
PLATFORM R COST	\$103M
SERVICING OPTIONS	1. Shuttle-based 2. Shuttle/OMV 3. Space Station Freedom /OMV 4. Expendable Servicing system

## **EXPENDABLE PLATFORM SCENARIO**

The expendable platform scenario assumes that each of the two science payloads are integrated and launched on expendable satellites. The assumption was made to use the existing MMS spacecraft as the expendable satellite since development of the MMS with EUVE is an existing mature design. It is conceivable that a new spacecraft design tailored to the weight, power, reliability, and lifetime of each science payload could be lower in cost. However, this would have taken a significant amount of effort to achieve the same confidence in the cost numbers. Also, the current approach will present a real comparison to the existing servicing architecture.

# EXPENDABLE PLATFORM SCENARIO

SPACE SYSTEMS/ LORAL



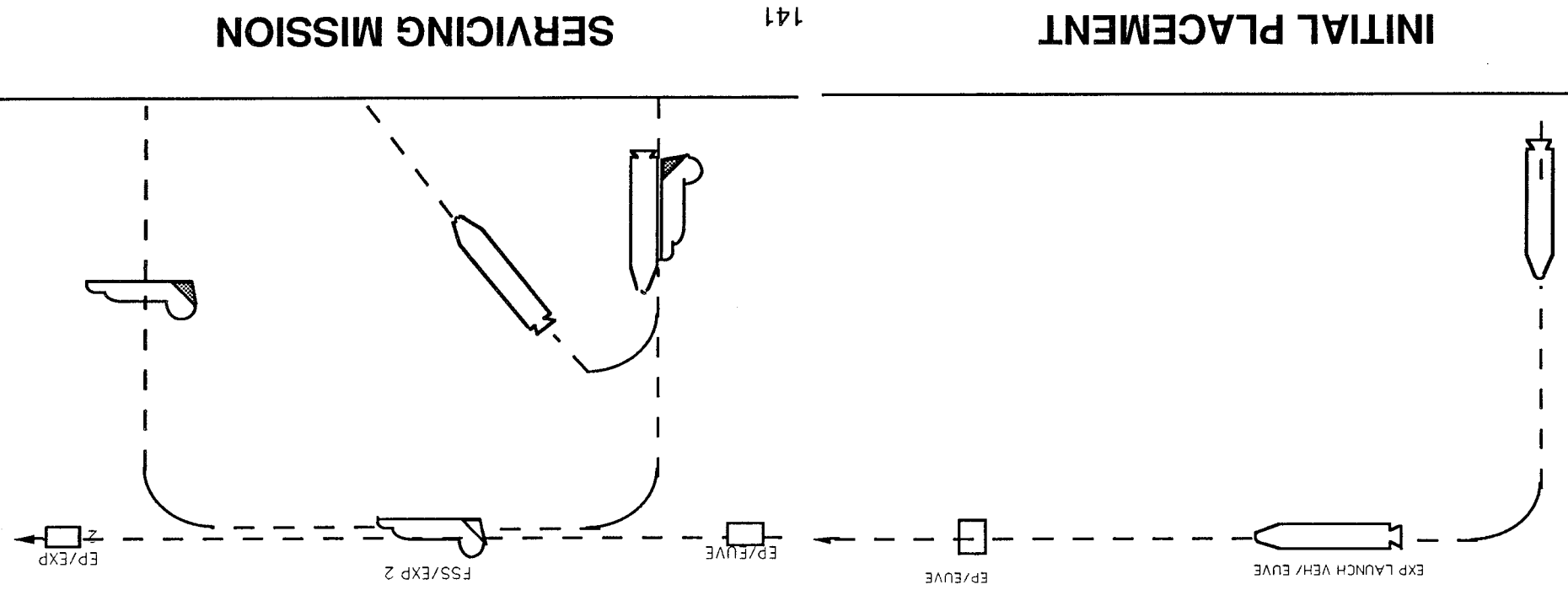
## **SHUTTLE BASED SERVICING SCENARIO**

This servicing scenario assumes the EP with the EUVE payload is on-orbit, having been launched with a Delta II launch vehicle. The new payload and any mission specific equipment is launched on the Shuttle to a nominal 330 nmi, 28.5° inclined orbit where the EP is retrieved by the Shuttle RMS. The old payload is removed and stowed on the FSS, and the new payload including any required MMS modules is installed.

The scenario assumes that the Flight Servicing system (FSS) is included in the Shuttle in order to stow servicing modules during launch and recovery, and to provide a servicing platform from which servicing is performed.

# SHUTTLE BASED SERVICING SCENARIO

SPACE SYSTEMS/ LORAL



SERVICING MISSION

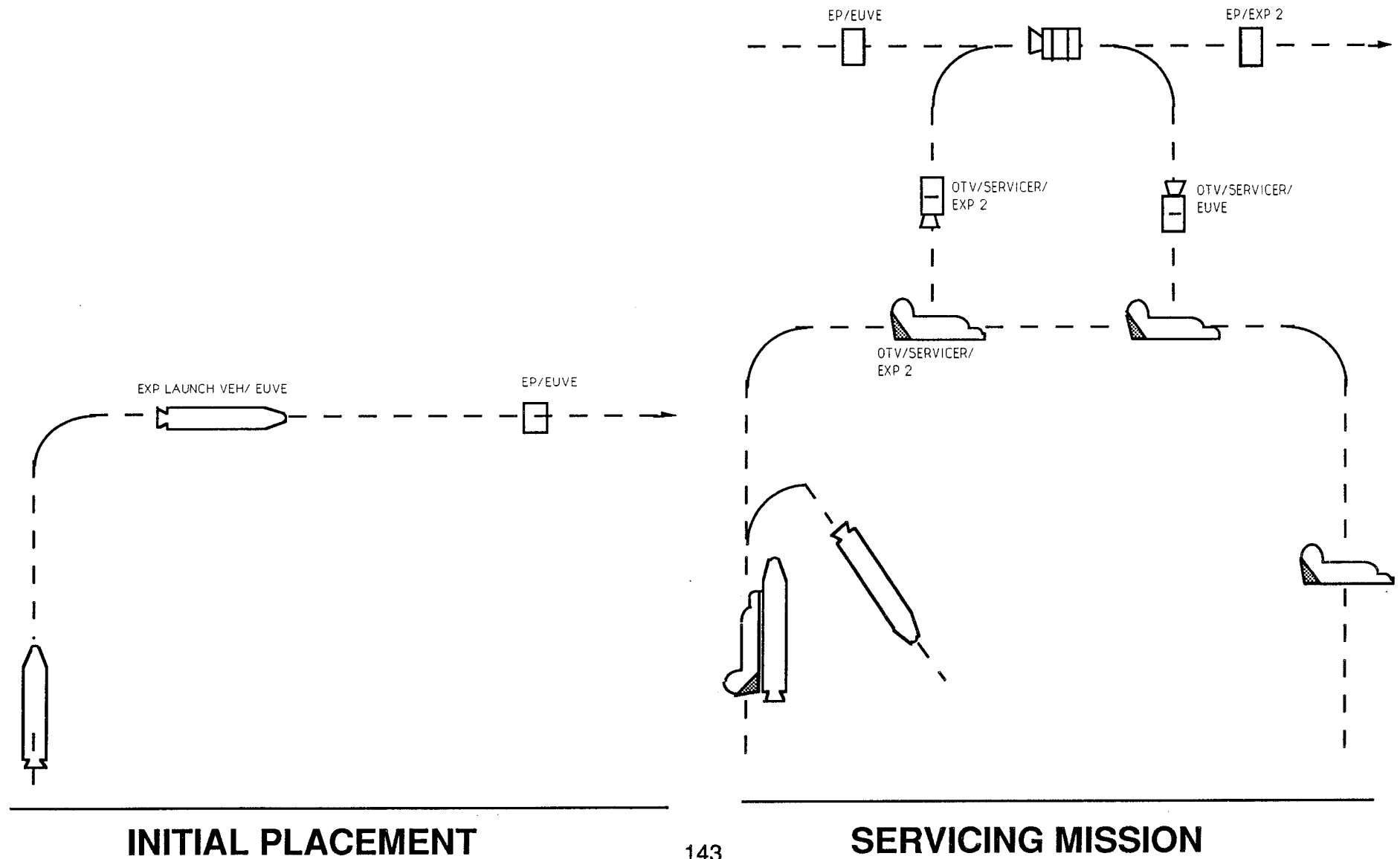
INITIAL PLACEMENT

## **SHUTTLE/OMV BASED SERVICING SCENARIO**

The Shuttle/OMV servicing scenario utilizes the OMV to transfer the new EP payload and mission specific equipment to the nominal EP orbit. The OMV/servicer is assumed to be carried in the Shuttle bay with the replacement payload to a nominal Shuttle orbit of 160 nmi. After separation from the Shuttle, the OMV performs the orbit transfer and rendezvous with the EP. The servicer kit, which is derived from Satellite Servicing System Program performs the necessary module replacements. The OMV then returns to, and is captured by the Shuttle for stowage and return to Earth.

# SHUTTLE/OMV BASED SERVICING SCENARIO

SPACE SYSTEMS/ **LOREAL**



## **SHUTTLE/ SPACE STATION FREEDOM BASED SERVICING**

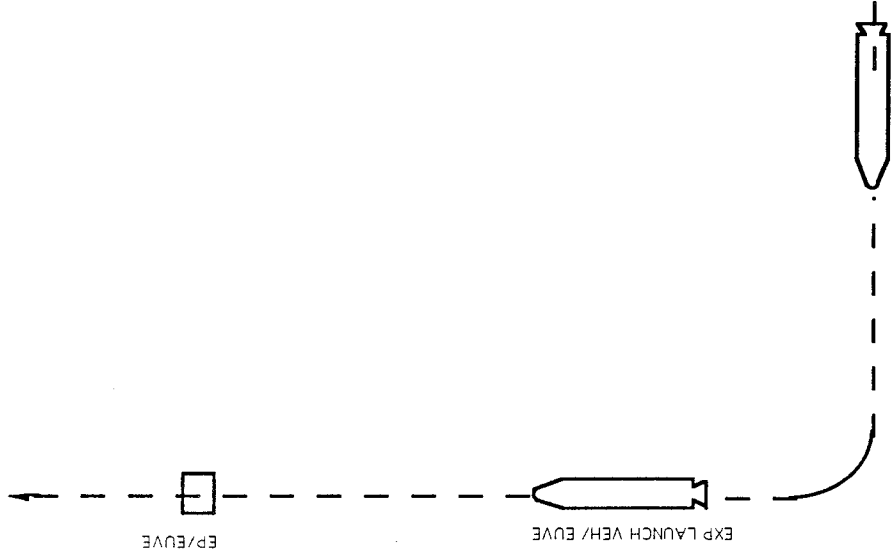
The Shuttle/SSF servicing scenario is a full implementation of the Space Transportation System (STS). The regularly scheduled Shuttle launch to Space Station Freedom (SSF) will transport the replacement payload, MMS modules, mission specific equipment, and propellant for the OMV. Payload handling, integration to the OMV, and checkout will be performed at SSF prior to launch of the servicing mission. The servicing mission consists of an optimized OMV transfer for rendezvous and docking with the EP, servicing of payload and required modules, and return to SSF.

The big impact of servicing from the Space Station is the logistics impact of payload handling and checkout, and integrating the payload to the OMV while on-orbit. The potential integration delay at the Space Station will quickly increase the propellant mass for orbit transfer to the EP orbit. However, a Shuttle servicing mission would be launched directly into the EP orbit.

# SHUTTLE/ SPACE STATION FREEDOM BASED SERVICING

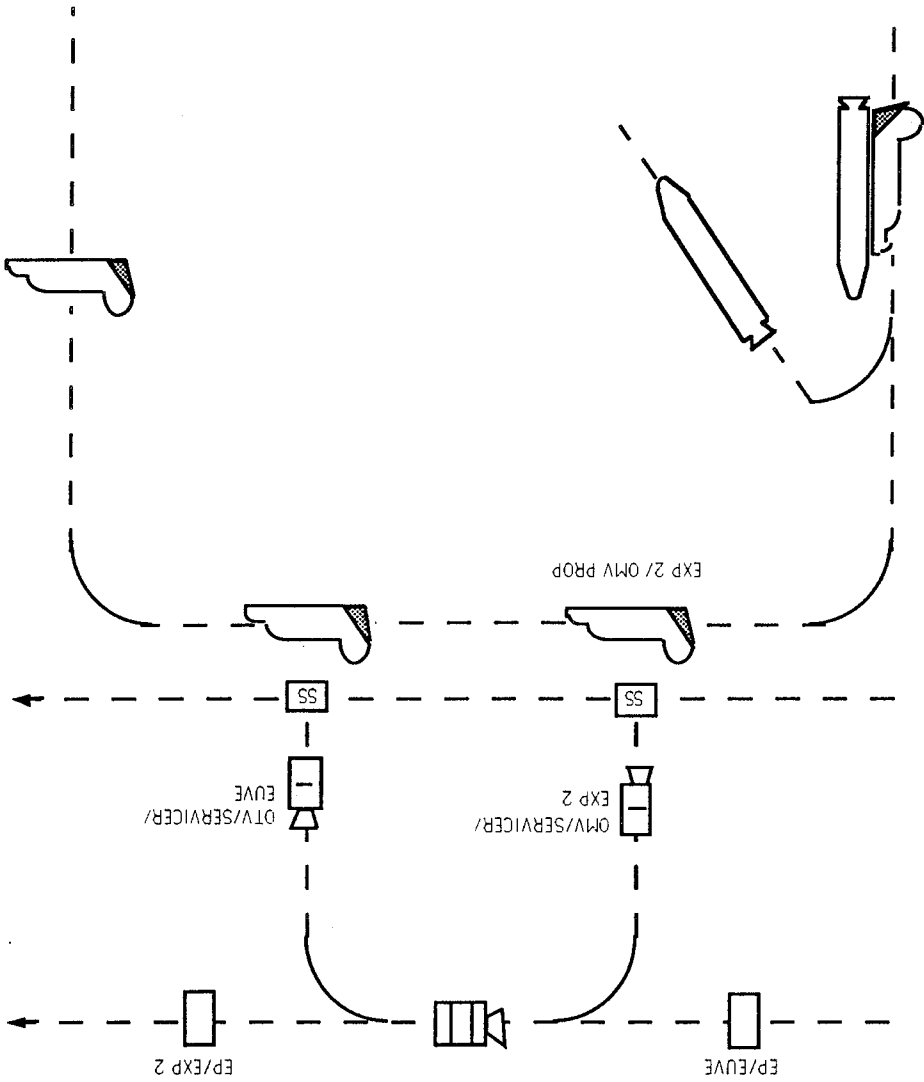
SPACE SYSTEMS/ LORAL

## INITIAL PLACEMENT



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## SERVICING MISSION



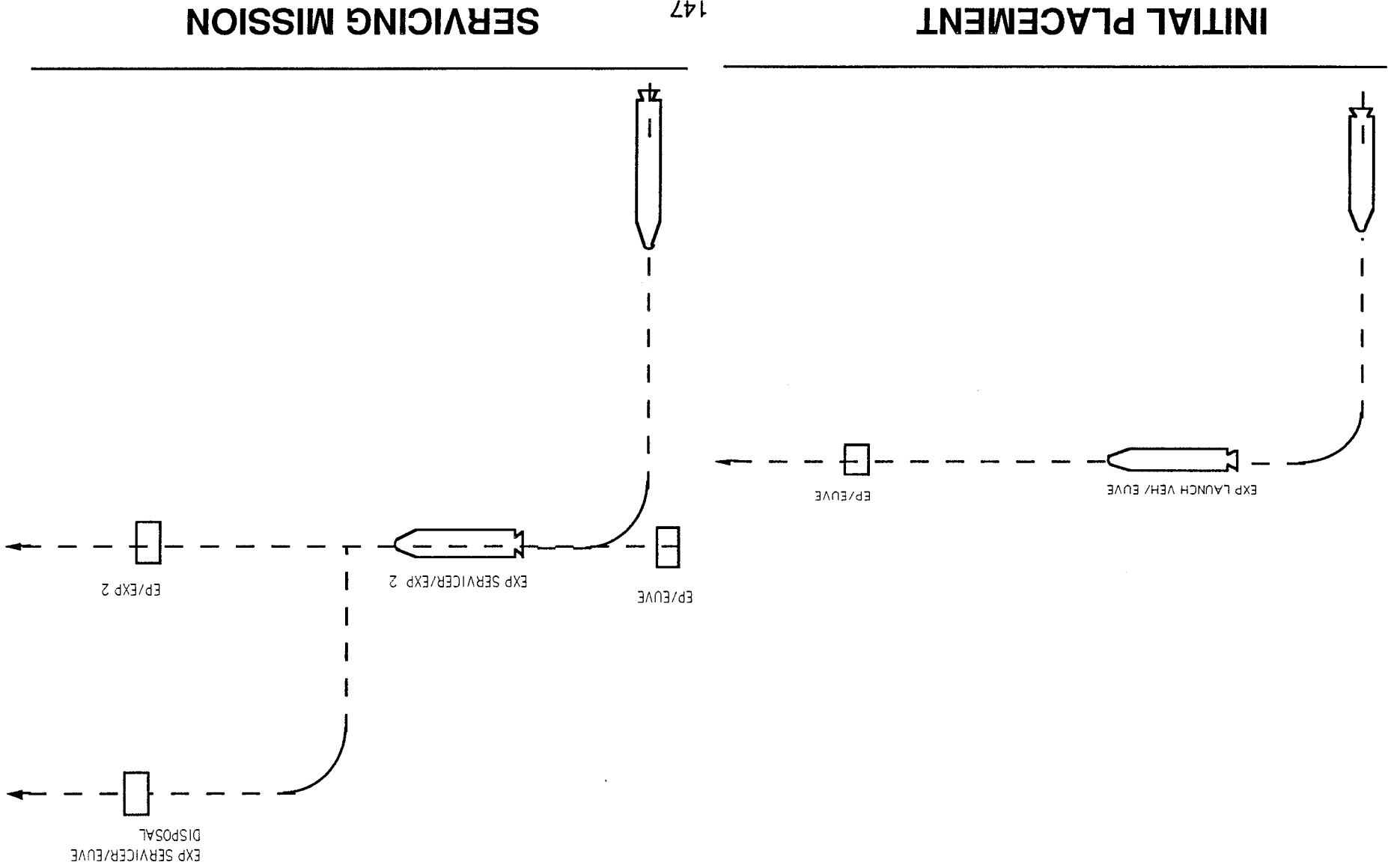
## **EXPENDABLE SERVICING SYSTEM (ESS) SCENARIO**

The expendable servicing scenario utilizes the autonomous features of the ESS to perform the required payload and module replacement. The ESS is launched into orbit with Delta II expendable launch vehicle. A significant benefit of this scenario is the daily launch window availability from a ground launched system. An orbit transfer from a space-based system is subject to significant waiting period between orbit nodal alignments. Any unexpected delay using space-based assets will result in significant propellant penalty required to perform the orbit transfer. A potential cost saving benefit also occurs from eliminating Shuttle and SSF related logistics support.

The potential drawback of the expendable servicing scenario is that if a failure occurs, the mission success may be compromised, and the expense of an entirely new servicing system or replacement platform will be required.

# EXPENDABLE SERVICING SYSTEM (ESS) SCENARIO

SPACE SYSTEMS/ **LOREAL**



## GENERAL EP ASSUMPTIONS

The platform and experiment probability of success data was not available. In-house assumptions were made. A P(s) of 0.92 was used for the EP bus at a 10 year mission life, and 0.96 was used for the experiment at a 3.5 year mission life.

For Modelling purposes, the platform and cumulative experiment expected lifetimes were not equal. The MMS has a 10 year design life, but not all of the experiments to fully utilize that capability have been defined, so the model executed just a single experiment replacement. The experiment titled, "Exp #2" is a simulation of the XTE payload, but no cost data was available, so a generic payload was assumed. The assumption on costs for the Exp #2 was assumed to be 1.2 times the EUVE experiment costs. Now, the implication of not modelling the Explorer Platform as a 10 year on-orbit program will not effect the accuracy of the servicing versus expendable platform comparison. The input to the SATCAV model only allows a single servicing mission definition. Therefore, the expected lifetime for both experiments was selected to be 3.5 years. The system mission lifetime ran for 7 years instead of 10 so that multiple servicing missions would not be triggered. The only implication by this modelling assumption is that since the MMS has a 10 year design life, no failures of the MMS would likely result.

The assumption was made, and accepted by MSFC, that the exclusion of Shuttle charges to NASA programs, because they are considered secondary payloads, would not accurately compare the servicing versus the expendable scenarios. This is mainly due to the fact, that most expendable satellites are launch on Expendable launch vehicles, and serviceable scenarios are serviced with the STS. Therefore, to compare scenarios with consistency, Shuttle launch costs were included. The chart to follow fully explains the Shuttle launch cost assumptions.

Some servicing versus expendable scenarios decrease the cost of the expendable satellite relative to the servicing one to try and adjust for the fact that a serviceable satellite is 10%-15% more costly to design and build. That assumption was not used for EP because MMS is an existing design that has flight history. The assumption was made that it would be more realistic of a comparison to compare all options with a common satellite bus.

# GENERAL EP ASSUMPTIONS

SPACE SYSTEMS/ **LORAL** —

- The experiment expected lifetime is 3.5 years
- A four year engineering development period prior to launch
- Delta II launch Vehicle for initial EP placement and expendable servicing missions
- EP spacecraft bus reliability 0.92 with a 10 year expected lifetime
- EUVE and Exp #2 reliability of 0.96 with a 4 year expected lifetime
- The NR and R cost of Exp #2 is 1.2 times that of EUVE
- The Shuttle launch charges are based on a sliding scale based on launch weight relative to launch capacity to orbit. The secondary payload approach is not considered
- The baseline EP is used for all servicing options. No platform discounting is applied, even for the expendable platform scenario.

## SHUTTLE LAUNCH COSTS

The methodology for generating Shuttle launch costs can be quite ambiguous, and one gets a different answer depending who answers the question. A typical method uses the payload weight and length occupied in the Shuttle bay to establish a percentage of the total launch cost. If the weight (which includes cradles and supports) is a higher percentage of the total than the length component, then the cost is based on weight instead of length. And similarly, the cost is based on the length if the percentage occupied is greater than the weight component. Additionally, if the percentage utilized is not greater than 75% of the Shuttle capacity (either weight or length, which is bigger) then a manifest charge, typically 33% of the payload launch cost, is added.

The individual NASA program offices do not recognize this cost as applied to their respective programs. They consider their manifest on the Shuttle as a secondary payload. In other words, they occupy excess Shuttle capacity, and therefore, the launch costs are not applied to their budget.

If this study adopted such an approach, the real cost comparison would be skewed to promote Shuttle-based servicing in all but polar orbits. Therefore, Shuttle launch charges using the methodology described above is used to generate a true cost comparison for the different servicing scenarios.

The baseline ground rule used to estimate Shuttle costs is based on a charge of \$208M to launch 56K lbs to a nominal orbit of 160 nm, 28.5° inclination. This results in a \$3714 per pound. Then for the various missions, a table look-up is used to determine the capacity for other than 160 nmi altitudes orbits. Then a new dollar-per-pound factor is determined. The 33% manifest charge is included for all EP Shuttle launches since the weight and length of the payload do not represent over 75% of the Shuttle capacity.

The weight estimates for all cradle and manifest weights were obtained from David Douds, GSFC.

# SHUTTLE LAUNCH COSTS

SPACE SYSTEMS/ **LORAL** —

PROGRAM LAUNCH	ALTITUDE NM	MANIFEST PAYLOAD	WEIGHT CRADLE	\$/LB	MANIFEST CHARGE %	SHUTTLE LAUNCH COST (\$M)
		(LB)	(LB)			
<b>Explorer Platform Servicing Mission</b> • FSS, Shuttle In-situ	330	5500	10,900	4,643	33	101.3
<b>Explorer Platform Servicing Mission</b> • Shuttle/OMV	160	18,000	5,000	3,714	33	113.6
<b>EP Servicing Mission</b> • Shuttle / SSF	240	11,950	8,400	4,020	33	109

## **EXPLORER PLATFORM SATCAV INPUT COSTS**

The input data for the EP has been acquired from two sources. Rudd Moe, Satellite Servicing Manager, GSFC, supplied the nonrecurring and recurring data for the MMS modules and the EUVE payload. Saroj Patel, MSFC supplied the remaining data. The data was converted into FY89 dollars. It was assumed for experiment #2 that the nonrecurring and recurring cost would be increased by 20% over the EUVE payload.

For all of the serviced and non-serviced scenarios, the same platform and platform costs are assumed. This is consistent with the philosophy that whether the platform is expendable or serviceable the same platform, as currently designed, would be used. Therefore, the same launch vehicle would also be used for initial placement of the platform. This reduces the cost comparison to the cost of the servicing mission and related launch costs relative to the platform replacement costs.

# EXPLORER PLATFORM SATCAV INPUT COSTS

SPACE SYSTEMS/ **LORAL** —

<i>EXPLORER PLATFORM</i>	<i>NON RECURRING</i>	<i>QTY</i>	<i>RECURRING</i>
EUVE	68.4	1	28.5
MMS	18.4	1	69.5
MACS	6.5		12.2
MPS	4.5		8.4
C&DH	7.4		13.1
SOLAR ARRAY & SADA			6.3
STRUCTURE			11.2
ODC			3.4
PROPULSION			5.1
TDRSS ANTENNA			4.0
FLT SOFTWARE			3.6
MISSION EQ DECK			2.2

## **EXPLORER PLATFORM SATCAV INPUT COSTS (cont)**

The following chart itemizes the major recurring cost inputs to the SATCAV model. In the expendable EP case, a replacement platform and payload is launched instead of servicing. It was assumed that for all repair scenarios that one MMS module (C&DH) would be replaced. The C&DH was assumed since tape recorders have a limited lifetime.

The Flight Support System (FSS) consists of three cradles which serves as an on-orbit servicing platform and provides mechanical and electrical interfaces between the EP and the shuttle. The FSS and launch support costs were acquired from S. Patel, MSFC. The FSS is utilized only for in-situ Shuttle based servicing scenario. In the Shuttle/OMV servicing case, it was assumed that the servicing modules would be stored on the servicer which is integrated to the OMV on the ground. In the SSF servicing scenario, the servicing payload is transported as cargo in the Shuttle to the space station.

The servicer and OMV costs were based on standard SSS and OMV user charges of \$5M and \$6M, respectively. The ESS servicer costs were derived from an internal study to develop a mission specific servicer. The \$20M recurring cost and \$7M NR assumes the design could draw on key technologies from previous programs such as the FTS, SSS, and OMV.

Space Station user fees were derived from in-space service and labor task estimating parameters obtained from S. Patel, MSFC. These charges include on-board EPS, DMS, Comm, astronaut services for up to 10 days, and SSF storage for up to 30 days.

Crew training costs assume such items as planning, procedures, and crew activity planning of personal and facilities. Also included, is mock-up, simulator design and construction costs required to adequately train the astronauts.

# EXPLORER PLATFORM SATCAV INPUT COSTS (cont)

SPACE SYSTEMS/ **LORAL** —

SERVICING COSTS	EP2	EP3	EP4	EP5
EXPERIMENT #2	34.2	34.2	34.2	34.2
EXPLORER PLATFORM C&DH MODULE	13.1	13.1	13.1	13.1
FLIGHT SUPPORT SYSTEM	6.0	---	---	---
FSS LAUNCH SUPPORT	2.2	---	---	---
USER GSE	1.7	1.7	1.7	1.7
SERVICER USER FEE	---	5.0	5.0	22
OMV USER FEE	---	6.0	6.0	---
CREW TRAINING	5.0	5.0	7.5	---
RMS/EVA	1.5	1.5	1.5	---
SPACE STATION USER FEE	---	---	7.0	---
	<u>63.7</u>	<u>66.5</u>	<u>76.0</u>	<u>71</u>

## EP BASELINE LCC SUMMARY

The following chart summarizes the LCC results for all expendable and serviceable scenarios. The total discounted LCC ranged from \$409M for the ESS servicing scenario to \$455M for the Space Station based servicing. The expendable servicer system (ESS) was the most cost effective from a bottom line cost stand-point. However, it was only 3.5% better than the expendable scenario, and 4.9% better than Shuttle-based servicing scenario. The level of confidence in this result cannot be very convincing due to the maturity of the cost inputs for a program (ESS) that is not very well defined. A more fundamental observation for the ESS scenario is the drastic difference in servicing system launch costs (ie. Delta II versus the Shuttle launch).

Typically, these studies use a 10% confidence threshold of the difference in total LCC to make conclusive comparisons. Such a comparison can be made for ESS versus the servicing scenario utilizing the space station. The total differential LCC is \$46M, and the 10% threshold is \$41M-\$45M; therefore, SSF-based servicing would not be cost effective relative to expendable servicing. However, the results of the other scenarios are too close to make conclusive recommendations.

A parametric method has been performed to extract useful trends relating to different servicing scenarios. The results of which are presented at the end of this section.

The output data indicate that 2.5 platforms are required for the expendable scenario, and that 1.1 platforms/1.3 servicing missions are required to maximize the overall availability over the 7 year mission lifetime. The interpretation of the number of platform or servicing mission, as shown below, is the modelling implementation of spreading the costs of a new platform or servicers. No modelling techniques are incorporated to stop the implementation of a new platform or servicer near end-of-life if a failure occurs., if a failure does occur near the end of the mission lifetime, then a percentage of the replacement cost is spread over the remaining mission years.

# EP BASELINE LCC RESULTS

SPACE SYSTEMS/ **LOREAL** —

	<u>INPUT DATA</u>				<u>OUTPUT DATA</u>		
	Satellite Cost (\$M)	Sat Launch Cost (\$M)	Repair Cost (\$M)	Servicing Launch Costs (\$M)	Discounted LCC	# SAT	# Repair Missions
EP 1 (Exp)	98	55	N/A	N/A	424	2.5	0
EP 2 (Shuttle)	98	55	63.7	101.3	430	1.1	1.3
EP 3 (Shuttle/OMV)	98	55	66.5	113.6	447	1.1	1.3
EP 4 (Shuttle/SSF)	98	55	76.0	109	455	1.1	1.3
EP 5 (Exp. Servicer)	98	55	71	55	409	1.1	1.4

- **The Expendable servicer demonstrated the lowest LCC**
- **However, scenarios EP1 and EP2 and EP5 were all within 5%, which is below the established 10% confidence factor**

## EP LCC COST COMPONENT

The following bar chart itemizes the undiscounted LCC components for each of the 5 scenarios. As expected, the S/C costs for the expendable scenario are approximately double the servicing scenarios. The servicing costs for the ESS are the highest because the servicer cost represents the entire recurring cost, were as only user fees, significantly below the recurring cost, are assumed for the STS-based servicing options.

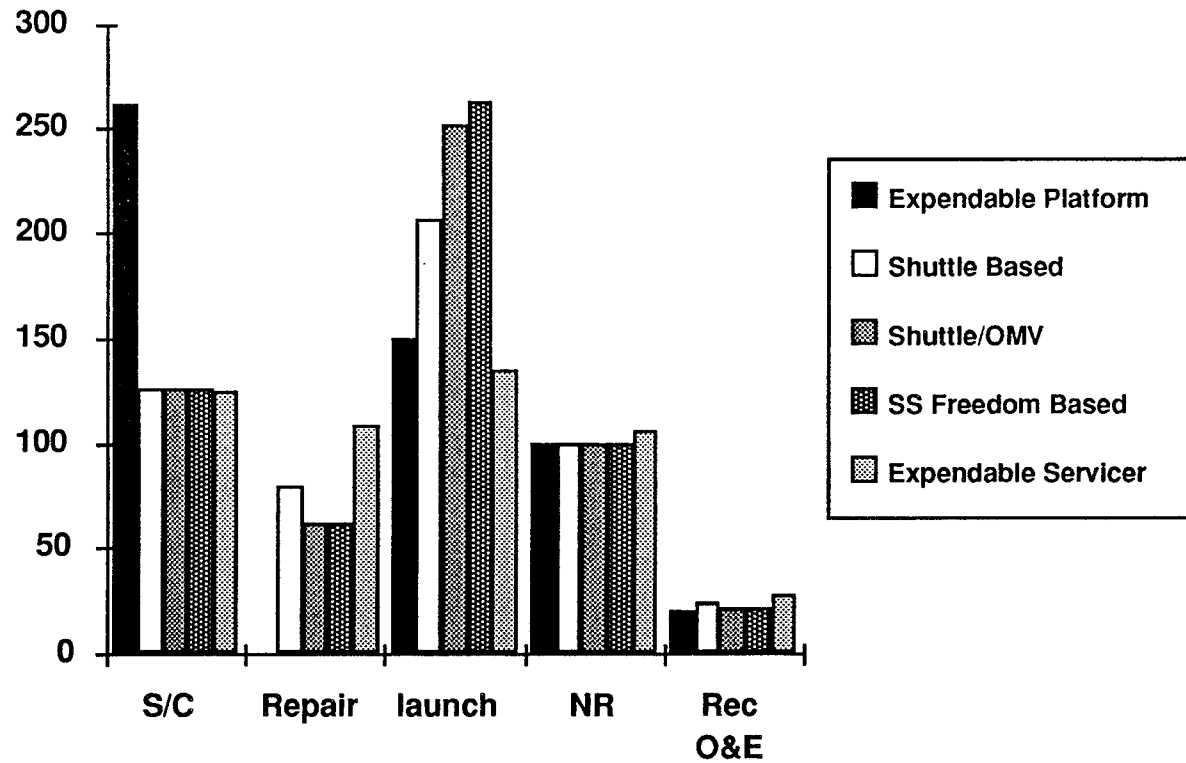
A slightly misleading observation could be made from this chart. It looks as if Shuttle/OMV-based and SSF-based servicing missions are much more cost effective than the other scenarios. This is not a correct observation because due to the modelling of the different phases of these servicing options, some of the servicing mission costs were included as a launch to orbit cost. And therefore, are totaled as a launch cost. This is clearly observed as the launch costs for these two options are significantly higher than the Shuttle-based servicing option.

The nonrecurring costs are nearly identical for all but the ESS scenario. This is true for the first four options because the identical MMS and experiments were assumed for each case. The added nonrecurring in the ESS case is due to the development costs of the expendable servicer.

The Rec O&E are the necessary expenditures for continuing engineering and on-orbit ground control of the platform.

# EP LCC COST COMPONENT

SPACE SYSTEMS/ **LORAL**



## **EP LCC COST COMPONENT (cont)**

The LCC costs for the EP Expendable scenario spanned 11 years; 4 years of development, and 7 years of active on-orbit performance. Although the MMS has a design life of 10 years, only two payloads missions were assumed for the servicing scenarios. Therefore, to remain consistent, the SATCAV model mission life parameter was 7 years for all EP cases.

If a failure occurred during launch, a new platform was launched. If a payload or platform failure occurred, a servicing mission would be initiated, if serviceable, to maintain system availability. The serviceable platform assumed a 90% factor for a successful servicing mission. No degradation of that factor was assumed after a successful servicing mission. If the platform could not be serviced, then a new platform would be launched. The stochastic nature of the model would simulate a failure through the Monte Carlo simulation and then the input cost spreading function would spread that cost over the preceding years.

The SATCAV model does not have the flexibility to null out a servicing mission near the end of mission life. For example, if a failure occurred 6 months before the second experiment was to be launched, the EUVE payload would be serviced and 6 months later the new experiment mission would be initiated. The only way to try and overcome this is to bump-up the Mean Time To Failure (MTTF) parameter so that no failure occurs prior to experiment replacement. Therefore, the MTTF for the experiment and the platform was set at 99 years and 120 years, respectively.

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## EP PARAMETRIC ANALYSIS INPUT PARAMETERS

The following chart shows the 4 parametric studies for the Expendable, Shuttle based, and Expendable servicer mission scenarios. It was felt that these 3 cases would adequately indicate the cost savings trends of servicing versus replacement platforms. The reliability parametric was not performed because no data was available in the baseline cases, and therefore, no data point existed from which accurate parametrics could be performed.

The WTR pad modification costs have been removed in the parametric study. This was mentioned in the baseline input section as a controversial cost. Although it was included in the baseline results, it has been removed in the parametrics.

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# EP PARAMETRIC ANALYSIS INPUT PARAMETERS

SPACE SYSTEMS/ **LORAL** —

PARAMETRIC CASES	PARAMETRIC 1 SATELLITE COST				PARAMETRIC 2 RELIABILITY		PARAMETRIC 3 SERVICER SYS. COST				PARAMETRIC 4 LAUNCH COST		
	PAYLOAD		REPAIR KIT		SENSOR	BUS	SERV KIT		LAUNCH CST T-3		NR	RECURRING	
	NR	R	NR	R	MTTF	MTTF	NR	R	NR	R	NR	T-1	T-3
EP 1 (Expendable)	±25%	±25%	-----	-----	-----	-----	-----	-----	-----	-----	-----	±20%	-----
EP 2 (Shuttle Based)	±25%	±25%	±25%	±25%	-----	-----	-----	±25%	-----	-----	-----	±20%	±20%
EP 5 (ExpServicer)	±25%	±25%	±25%	±25%	-----	-----	±25% Serv	±25%	-----	-----	-----	±20%	±20%

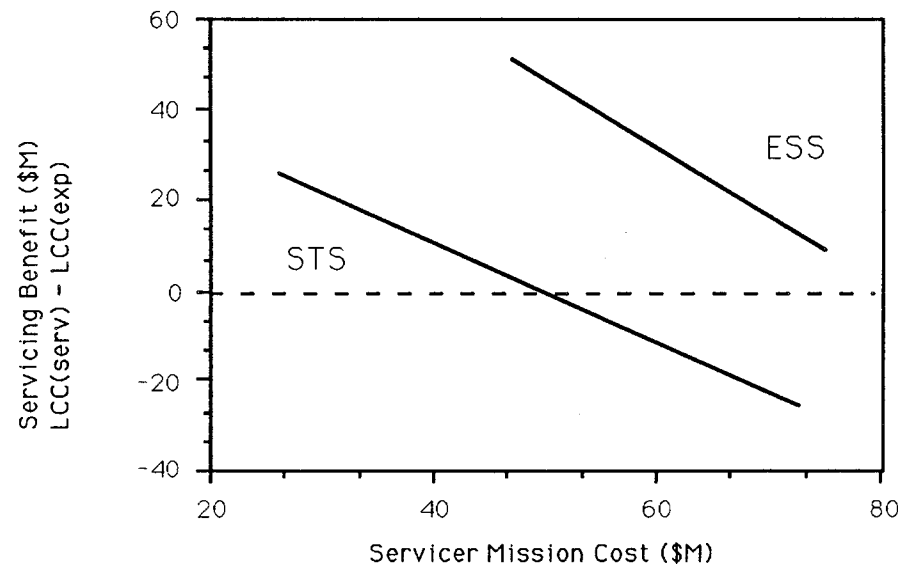
## EP SERVICER COST PARAMETRIC

The graph on the facing page illustrates the impact of repair kit cost on the relative economic benefits of servicing. The differential LCC is the difference between the indicated servicing option versus a corresponding expendable spacecraft. When the differential LCC is below zero, it indicates that a non-serviced, replacement spacecraft scenario is the most cost effective.

The plot shows that servicing is marginally cost effective for the Expendable Servicing System (ESS), with a break even servicer cost of approximately \$80M. The baseline servicer cost for ESS was \$54M. The break even point for Shuttle based servicing is much lower than the ESS case, approximately \$50M. The primary reason is the much higher Shuttle launch costs which significantly impact the total LCC.

# EP SERVICER COST PARAMETRIC

SPACE SYSTEMS/ **LORAL**



- Differential LCC benefits for each of the servicing options are shown as a function of EP servicing kit recurring cost by varying both the nonrecurring and recurring costs
- The ESS servicing option shows LCC savings benefits over the expendable scenario for servicing kit costs below \$80M
- Shuttle based servicing becomes cost effective over the expendable scenario when servicing kit costs are below \$50M.
- The lower slope STS curve results from fact that launch costs represent a higher percentage of the total LCC than the ESS case

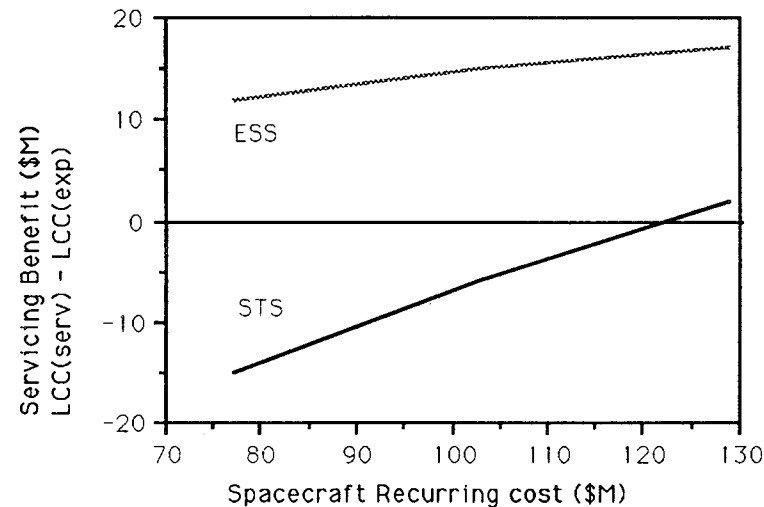
## EP SPACECRAFT PARAMETRIC

The graph on the facing page illustrates the impact of satellite cost on the relative economic benefits of servicing. The differential LCC is the difference between the indicated servicing option versus a corresponding expendable spacecraft. When the differential LCC is below zero, it indicates that a non-serviced, replacement spacecraft scenario is the most cost effective.

The plot shows that servicing is marginally cost effective for the ESS and increases slightly with increasing satellite cost. The STS servicing mission is not cost effective until the satellite cost increases to over \$122M. The baseline EP cost is \$98M.

# EP SPACECRAFT PARAMETRIC

SPACE SYSTEMS/ **LORAL** —



- This chart shows the Differential LCC cost variations versus spacecraft recurring cost by varying the NR and R data for both the spacecraft and servicer
- The trend of chart indicates that as the spacecraft R cost increase, the potential benefits of servicing increase. Even though the servicer costs are also increasing with spacecraft costs, this trend is valid when the spacecraft replacement costs are much greater than the servicing kit costs
- The greater the difference between the spacecraft replacement and servicer kit costs, the steeper the slope of the curve.

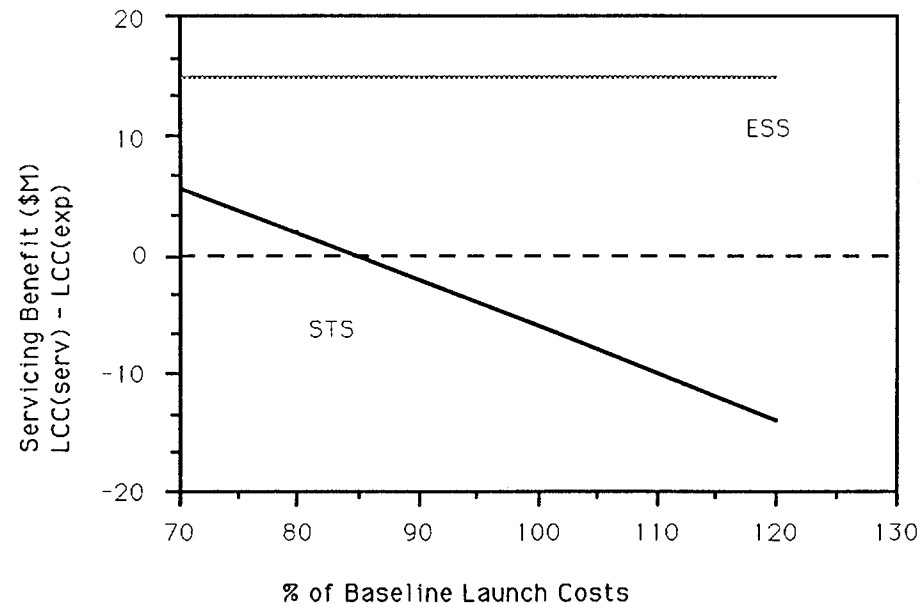
## EP LAUNCH COST PARAMETRIC

The graph on the facing page illustrates the impact of launch cost variation on the relative economic benefits of servicing. The differential LCC is the difference between the indicated servicing option versus a corresponding expendable spacecraft. When the differential LCC is below zero, it indicates that a non-serviced, replacement spacecraft scenario is the most cost effective.

The plot shows that launch costs have no relative LCC impact on the ESS. This is not a significant result. It appears constant because the ESS and the Expendable EP scenarios both utilize the same launch vehicle. Thus, a launch cost percentage change in both scenarios results in no relative difference. However, a launch cost percentage change in the Shuttle costs versus the expendable scenario will result in a marginal change in LCC, as shown below. When the Shuttle costs are decreased by 15%, the break even point in relative LCC is reached.

# EP LAUNCH COST PARAMETRIC

SPACE SYSTEMS/ **LORAL** —



- Differential LCC is the expendable minus the serviceable case
- ESS is constant because both the Expendable and the ESS assume the Delta II launch vehicle
- A servicing option benefit using the Shuttle is observed for launch costs below 85% of nominal, or \$85M

## EXPLORER PLATFORM SUMMARY

The expendable servicer system (ESS) was the most cost effective from a bottom line cost stand-point. However, it was only 3.5% better than the expendable scenario, and 4.9% better than Shuttle-based servicing scenario. The level of confidence in this result cannot be very convincing due to the maturity of the cost inputs for a program (ESS) that is not very well defined. A more fundamental observation for the ESS scenario is the drastic difference in servicing system launch costs (ie. Delta II versus the Shuttle launch).

Typically, these studies use a 10% confidence threshold of the difference in total LCC to make conclusive comparisons. Such a comparison can be made for ESS versus the servicing scenario utilizing the space station. The total differential LCC is \$46M, and the 10% threshold is \$41M-\$45M; therefore, SSF-based servicing would not be cost effective relative to expendable servicing. However, the results of the other scenarios are too close to make conclusive recommendations.

The parametric analysis generated some important, but not terribly surprising trends. It was shown that as servicer costs decreased, the benefit of servicing increased. They also showed that as the platform cost increased, the benefit of servicing increased. The launch cost parametric indicated that if the Shuttle launch costs could be reduced by 15%, then a break even point for Shuttle-based servicing would occur relative to the expendable platform.

Although it was stated that no conclusive recommendations could be made to rank the top three scenarios, the parametrics do allude to a few important observations. First, with the current Shuttle costs it is almost impractical to achieve a 10% servicing benefit over the expendable scenario. And second, the only reason that the ESS trends are so encouraging over the Shuttle-based servicing option, is because of the launch cost disparity. So although the parametric trends indicate where the break even points appear, the value of the Shuttle launch costs are the single most influential factor as to how the results appear.

# EXPLORER PLATFORM SUMMARY

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SPACE SYSTEMS/ **LOREAL** —

- The total LCC for all the EP scenarios ranged between \$409M and \$455M, a 10.6% difference. The 3 most cost effective scenarios were within \$21M; the Expendable servicer (\$409), the Expendable platform (\$424M), and the Shuttle based servicer (\$430M).
- The results do not indicate a clear advantage for either the servicing or expendable scenarios. However, the data supports the conclusion that SSF-based servicing is not cost effective, and has a much higher probability of increased costs if on-station delays occur.
- The SATCAV model results are highly dependent on reliability data to estimate failure probabilities. Since no data was available, the accuracy of the results is suspect. However, the relative difference is still representative since most of the same hardware was assumed for all mission scenarios.
- The parametric study trends indicate that as repair kit and launch costs are reduced, the benefit of servicing the platform increases. And as the total spacecraft system cost increases, the benefit of servicing also increases, as long as the servicing kit costs are significantly lower than spacecraft replacement cost.

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# POP, AXAF, EP CONCLUSIONS

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## **AXAF, POP, EP SUMMARY**

The following chart summarizes the satellite, servicer, and total LCC for the most cost effective servicing option for each of the DRMs analyzed.

The EP/ESS scenario utilizes the autonomous features of an envisioned expendable servicer to perform the required payload and module replacement necessary to service the platform. The ESS is launched into orbit with Delta II expendable launch vehicle. The platform cost of \$98M includes the MMS, EUVE payload, and mission specific equipment. The servicer cost of \$71M includes an XTE similar payload (assumed at 1.2 times the cost of EUVE), a replacement C&DH MMS module, and expendable servicer. A total LCC for one platform and two experiments over a 7 year mission life is \$409M.

The POP/Robotic Exchange servicing scenario also utilizes an expendable servicer to rendezvous and dock with the platform, however, a reusable robotic system is transported to the platform on the first servicing mission and is stored on the platform for future ORU robotic replacement. The service carrier undocks from the platform with the old sensors, and maneuvers to a disposal orbit. The platform cost of \$735M includes \$299M for the platform bus with integration, \$300M for the science payload, and \$100M for payload integration to the platform.

# AXAF, POP, EP SUMMARY

SPACE SYSTEMS/ **LORAL** —

PROGRAM	Satellite Cost (\$M)	Servicer Cost (\$M)	LCC Cost (\$M)
AXAF (ESS)	525	319	1938
EP (ESS)	98	71	409
POP (Robotic Exch.)	734	500	3502

## NEW DRM COMPARISON TREND

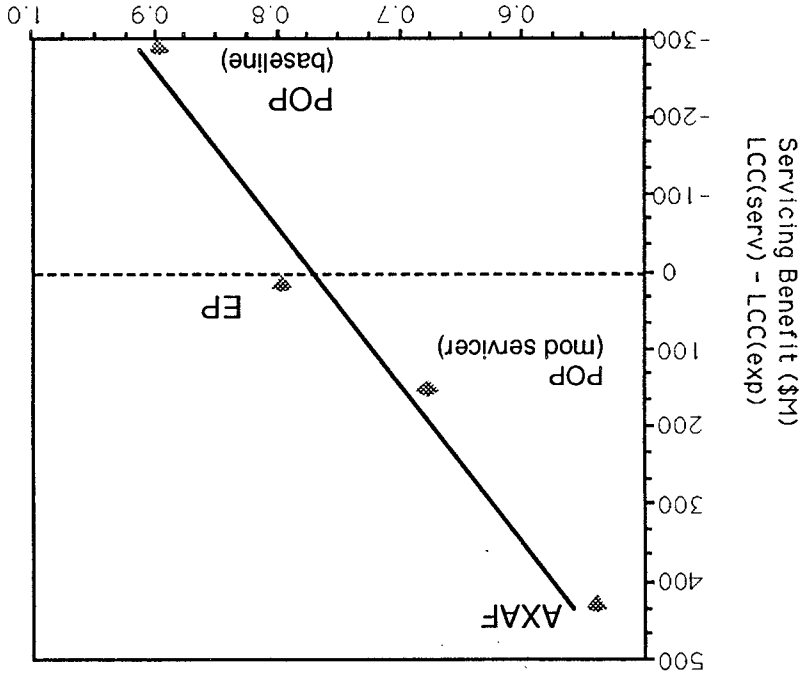
This summary chart comparing the three DRMs is an attempt to quantify a parameter that will be representative of new servicing missions. In sifting through the mass of data that this study generated, we felt that the ratio of servicer with launch costs to replacement satellite with launch costs captured the most influential parameters of a typical servicing mission. The differential LCC cost is the difference between the serviced spacecraft LCC and the unserviced spacecraft LCC. The data points for each DRM represent the scenario of greatest servicing benefit. In the case of the POP, two cases are shown since the baseline cases did not show any servicing benefits. The modified POP scenario represents a servicing mission in which not all of the science payload is replaced. For more detail see the POP parametric section.

The chart indicates that for systems with ratio value of less than 80% a servicing benefit exists. The lower the percentage of servicer to replacement cost, including launch costs, the greater the potential servicing benefit.

An attempt was made to expand this chart to include data from task 1. Although the overall trend was consistent with the new DRMs, the scatter in the data was quite large.

# NEW DRM COMPARISON TREND

SPACE SYSTEMS/ **LOGICAL**



- It was found that the ratio of servicer to replacement cost, including respective launch costs, is a good parameter to indicate the potential benefit of servicing.
- The approximate break even value of this parameter occurs between 80-82%. The lower the percentage of servicer to replacement cost, the greater the potential servicing benefit. This trend should be considered a good indicator for the design of new servicing missions.

# **SSES SUMMARY**

SPACE SYSTEMS/ **LORAL** —

- **Task 1 reviewed 14 old NASA servicing studies, and analyzed them with a common set of servicing and economic parameters.**
  - **The average savings in life cycle cost due to servicing is 19.6%.**
  - **The results of the 1989 analysis track previous results, thus validating the SATCAV model for new DRMs.**
  
- **Task 2 and Task 3 defined 3 DRMs: AXAF, EP, and POP. Each DRM examined the Expendable satellite versus Expendable Servicing, Shuttle Servicing and SSF Servicing. Shuttle servicing to polar orbit for the POP was not an option.**
  - **The data supports the conclusion that SSF-based servicing is not cost effective.**
  - **The servicing window of opportunity from SSF is small, and the waiting period before nodal alignment is large. This results in longer lead time planning to ensure window of opportunity is not missed, thus increasing servicing related costs.**
  - **Shuttle launch costs, as calculated, were significantly higher than the corresponding expendable launch vehicle. This factor greatly reduced any potential servicing benefits.**

## **SSES SUMMARY (con't)**

SPACE SYSTEMS/ **LORAL** —

### **DRM RESULTS**

- **AXAF:**
  - All of the considered servicing scenarios showed to be cost effective over the expendable AXAF scenario. The expendable servicing system resulted in the lowest LCC
- **POP**
  - Platform servicing was not cost effective if total payload replacement is a requirement. A modified servicing strategy was defined to investigate when POP servicing would be cost effective.
- **EP**
  - The Expendable servicer demonstrated the lowest LCC. However, the Expendable servicer, Shuttle based servicer (FSS), and the expendable satellite scenarios were all within 5% in total LCC.

# **FUTURE STUDY OPTIONS**

SPACE SYSTEMS/ **LORAL** —

- **The method of treating failures in a multi-purpose spacecraft can be treated in two ways. Either a system level reliability number can be used, or the SATCAV model has the capability to input a multi-payload set and track the failures of each. The present study incorporated the simpler method, but a more detailed analysis could be used in two ways.**
  - A) It could be used to help define a servicing strategy for a multi payload system. Since each payload would input its specific expected lifetime and failure probabilities, a time history of predicted failures and overall system availability could be tracked.**
  - B) Another useful characteristic of this analysis is to generate sets of specific servicing strategies. This is based on payload priorities, or perceived priorities. For example, reliability data is input for each payload (or even payload subsystems), then a matrix is created to specify what combination of payload failures should trigger a servicing mission. By running a few different failure combinations and comparing this with the associated LCC, a powerful payload discriminator parametric has been generated.**

# FUTURE STUDY OPTIONS

SPACE SYSTEMS/ **LORAL** —

- The Reliability Parametric demonstrated that a unique combination of redundancy and servicing will result in the lowest LCC. However, the analysis to estimate the reliability and associated spacecraft and servicer costs could be improved and expanded upon. This results could be further parameterized to show the sensitivity as a function of various subsystems. The servicing missions could also be parameterized and plotted together with the reliability data to indicate a set of optimal solutions for each redundancy scenario.
- New DRMs can be run or modifications to existing DRMs can be made. We feel that we understand our processes quite well and have now developed good communications with the NASA to obtain needed information. Therefore, we estimate over a 50% learning curve could be applied to subsequent analysis.

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